

Hadron Production and Neutrino Beams

- A survey of HP interactions
- Reweighting with thin target data
- Reweighting with NuMI target data

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LBNE Physics Workshop
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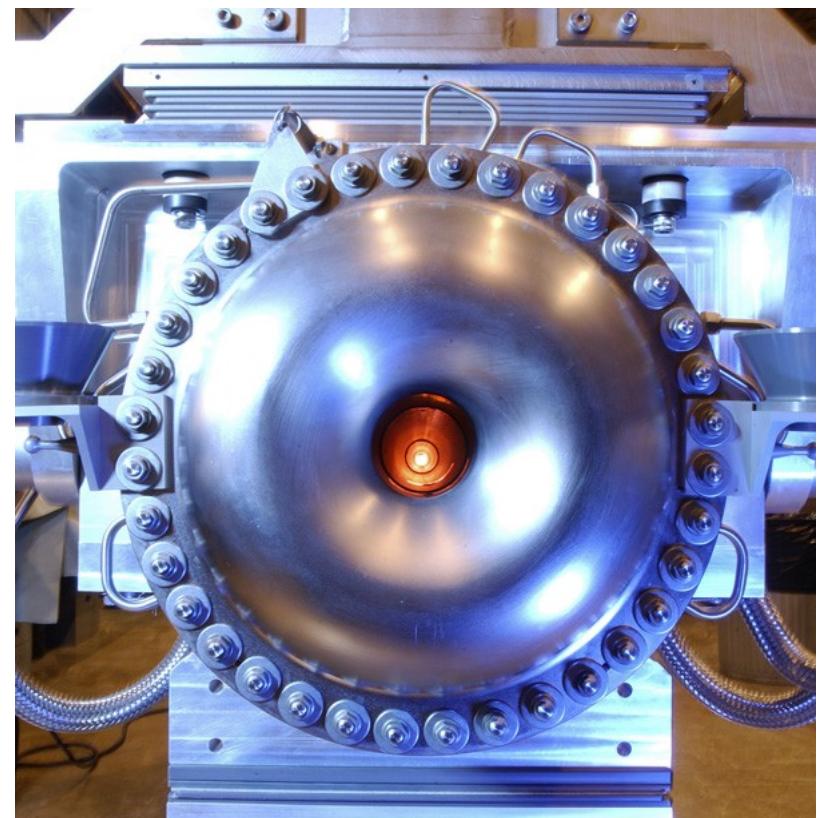
Where are mesons created?

Geant4 based simulation of the NuMI beamline

Origin of π^+ which produce
 ν_μ hitting MINOS/MINERvA

Target Fins (84.4%) +	89.0%
“Budal” Monitor (4.6%) [C]	
Decay Pipe Walls [Fe]	2.6%
Target Hall Chase [air]	2.2%
Decay Pipe [He]	1.8%
Horn 1 Inner Conductor [Al]	1.5%
All other summed	2.9%

Z. Pavlovic, L. Loiacono,
J. Ratchford, J. Koskinen,
M. Jenkins, T. Le, et al.

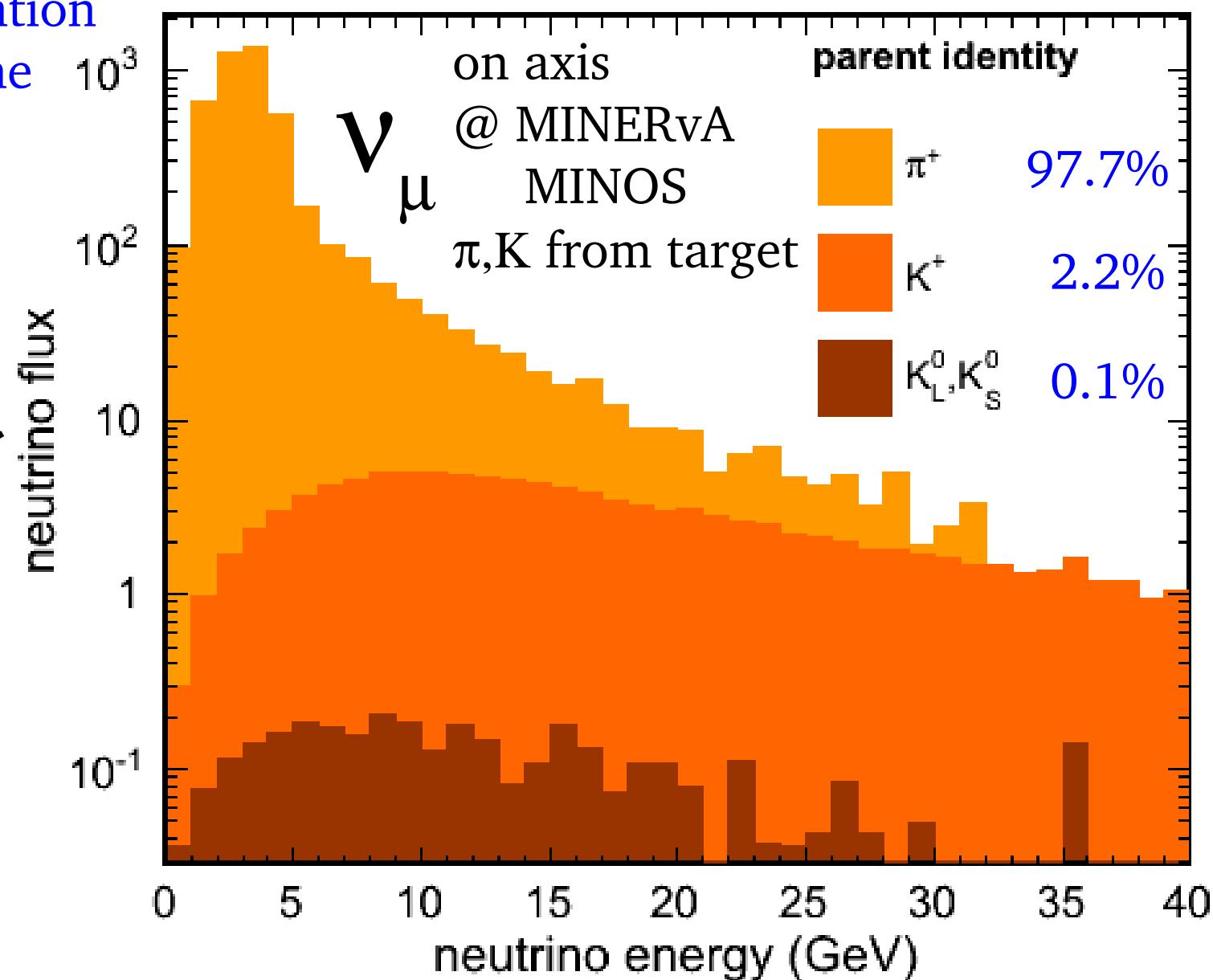


Predicted Neutrino Flux

Geant4 based simulation
of the NuMI beamline

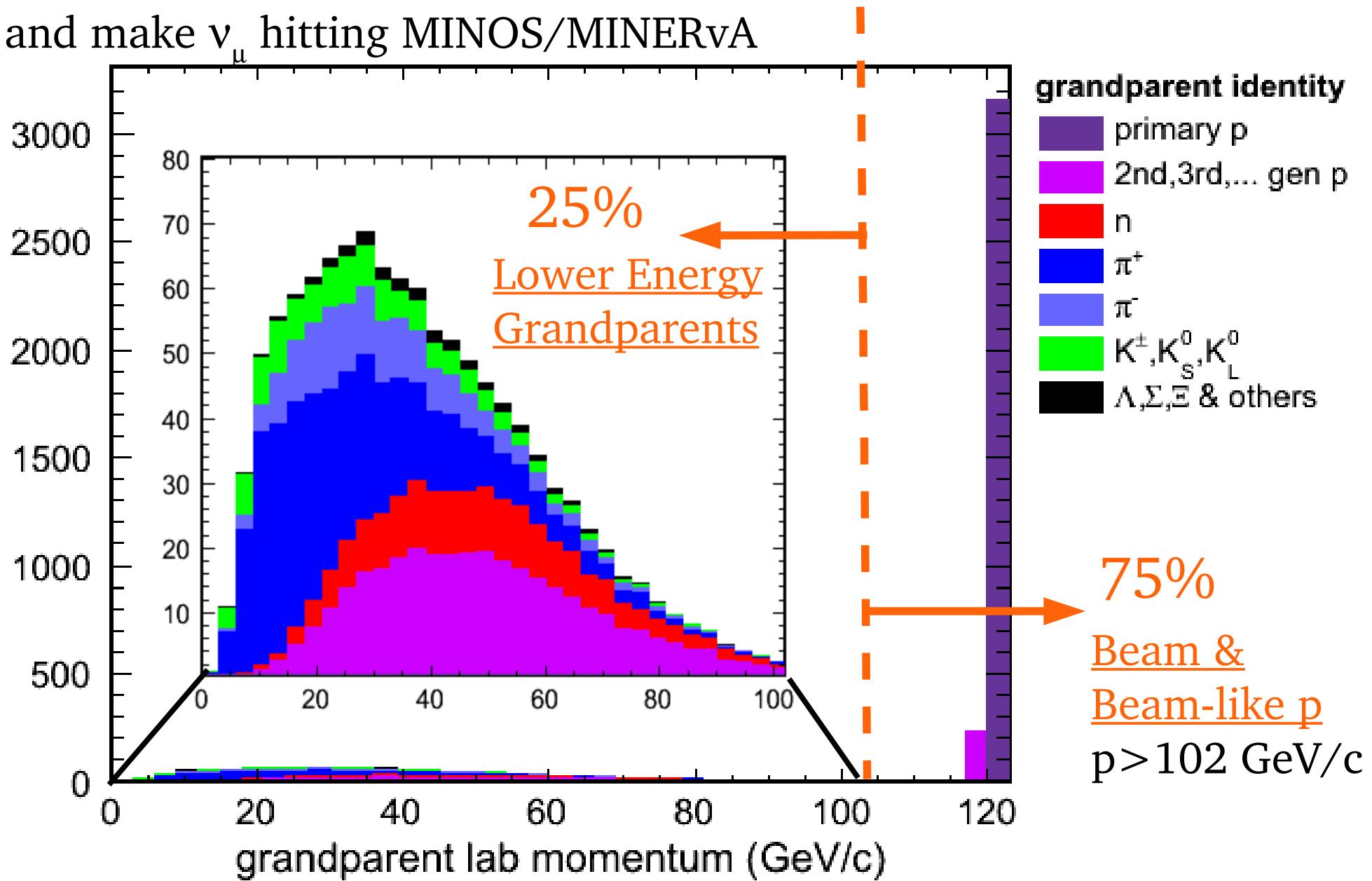
Z. Pavlovic, L. Loiacono,
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Event Rate
 $\sim 50k \nu_\mu$ -CC
for 1t plastic
and 1×10^{20} POT

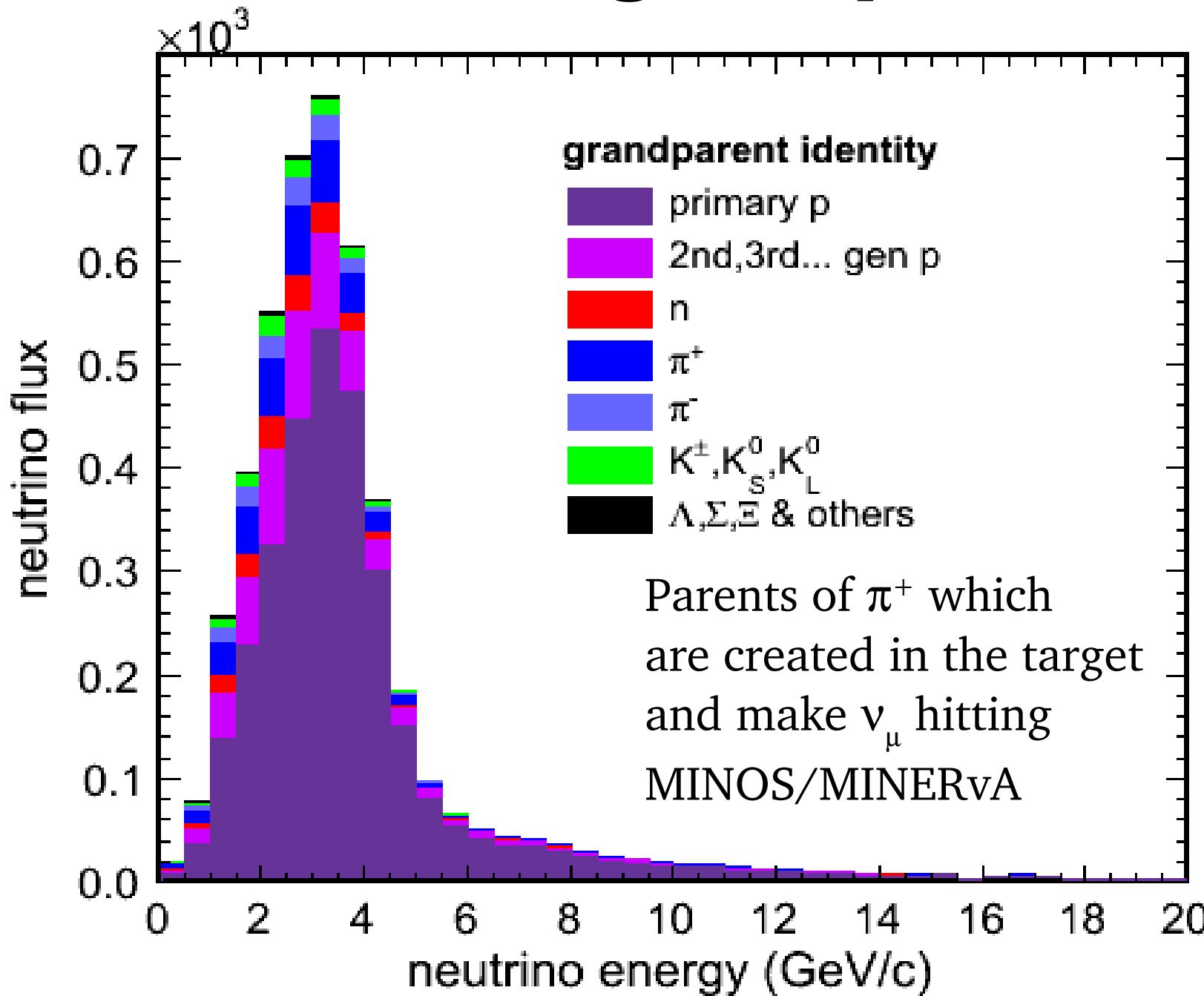


Neutrino grandparents?

Parents of π^+ which are created in the target
and make ν_μ hitting MINOS/MINERvA

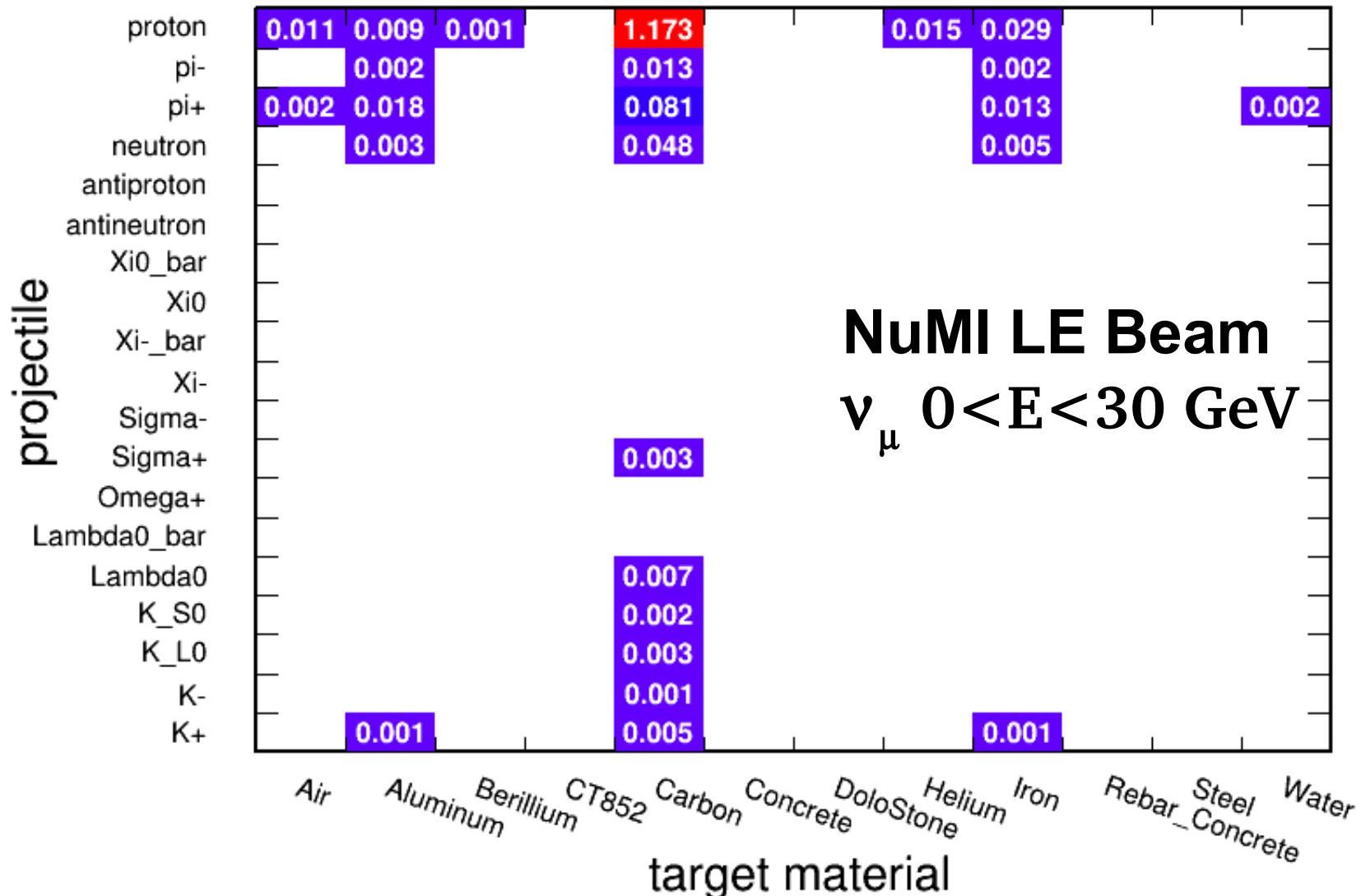


Neutrino grandparents?

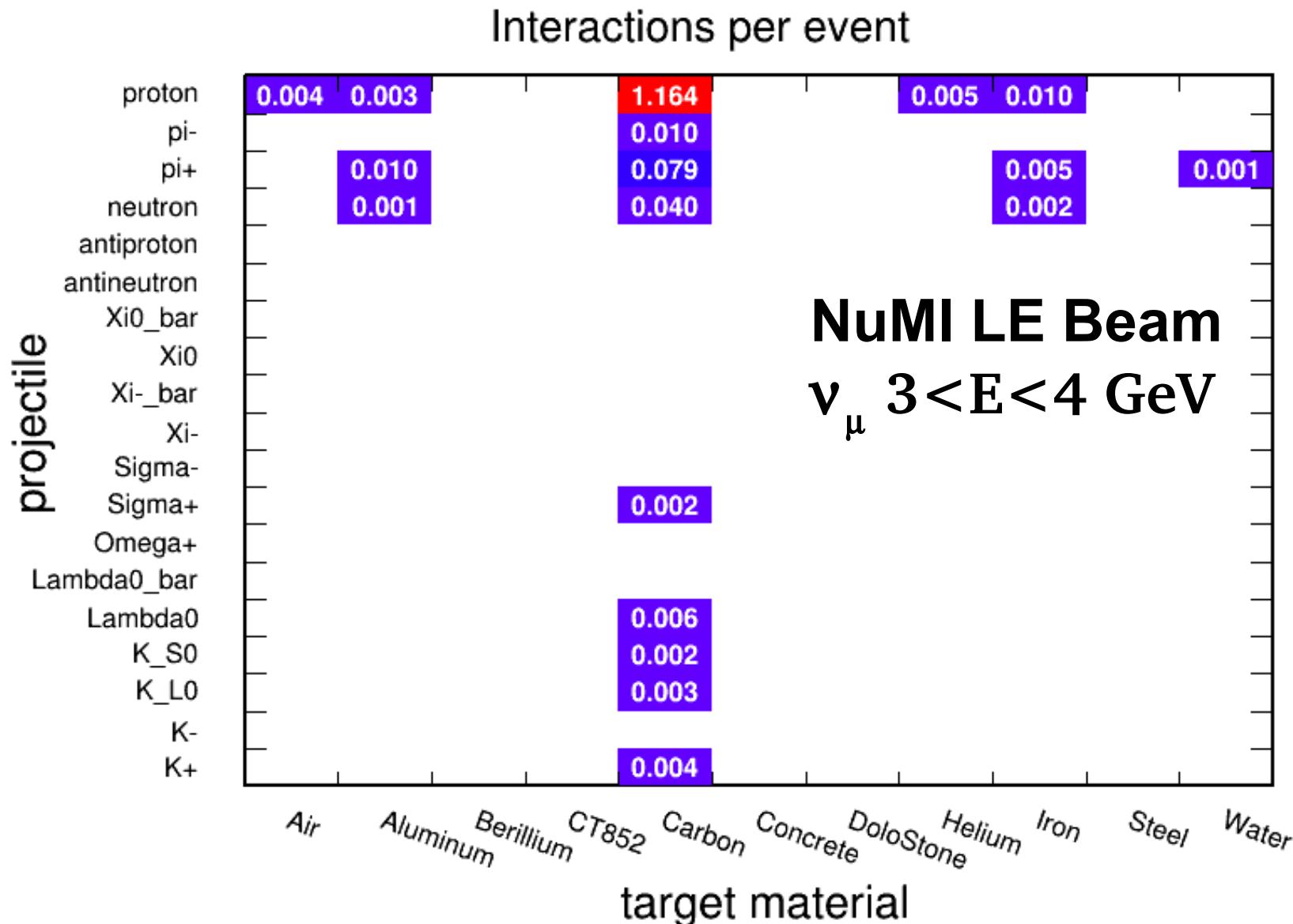


An interaction map

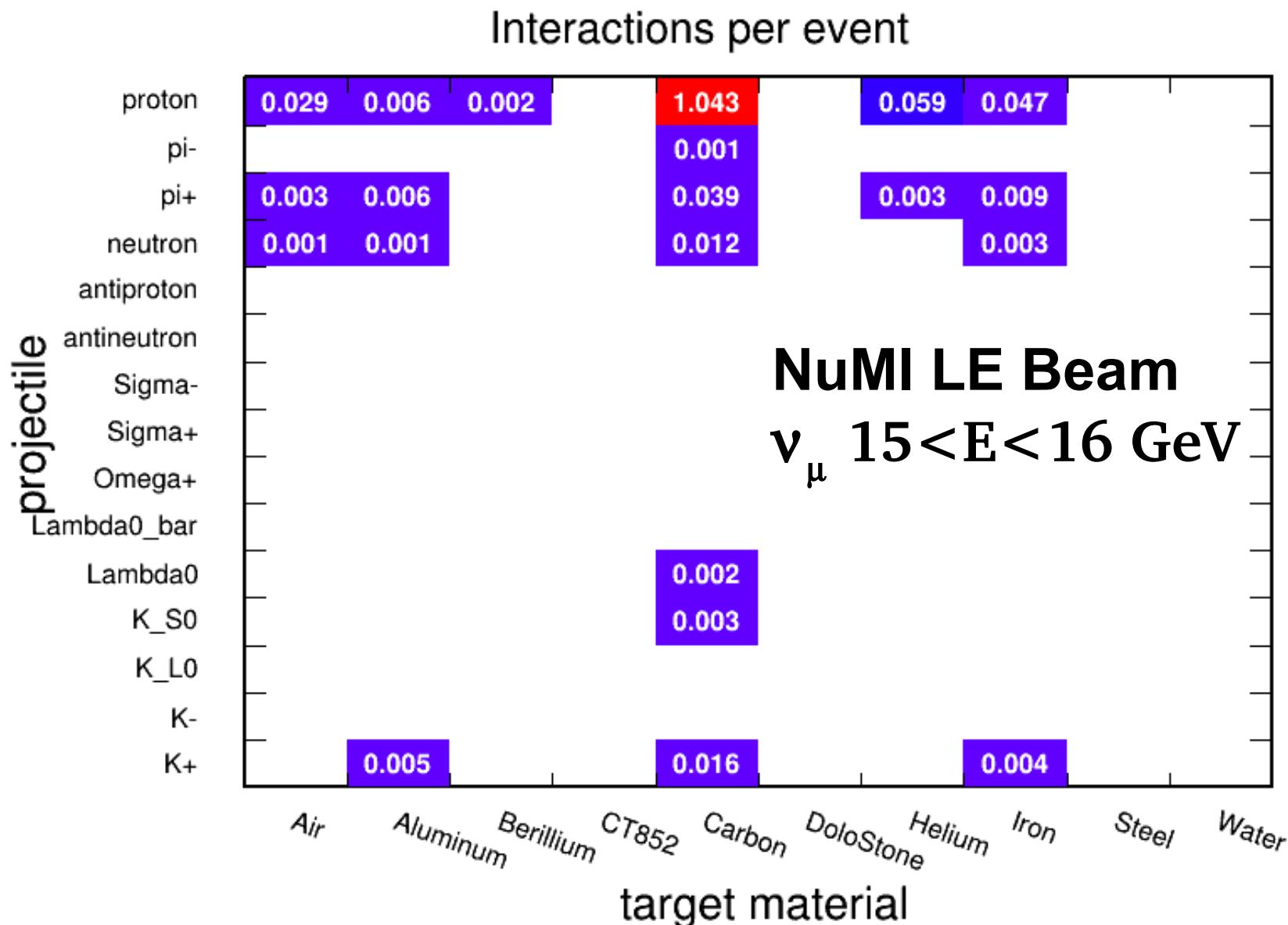
Interactions per event



An interaction map

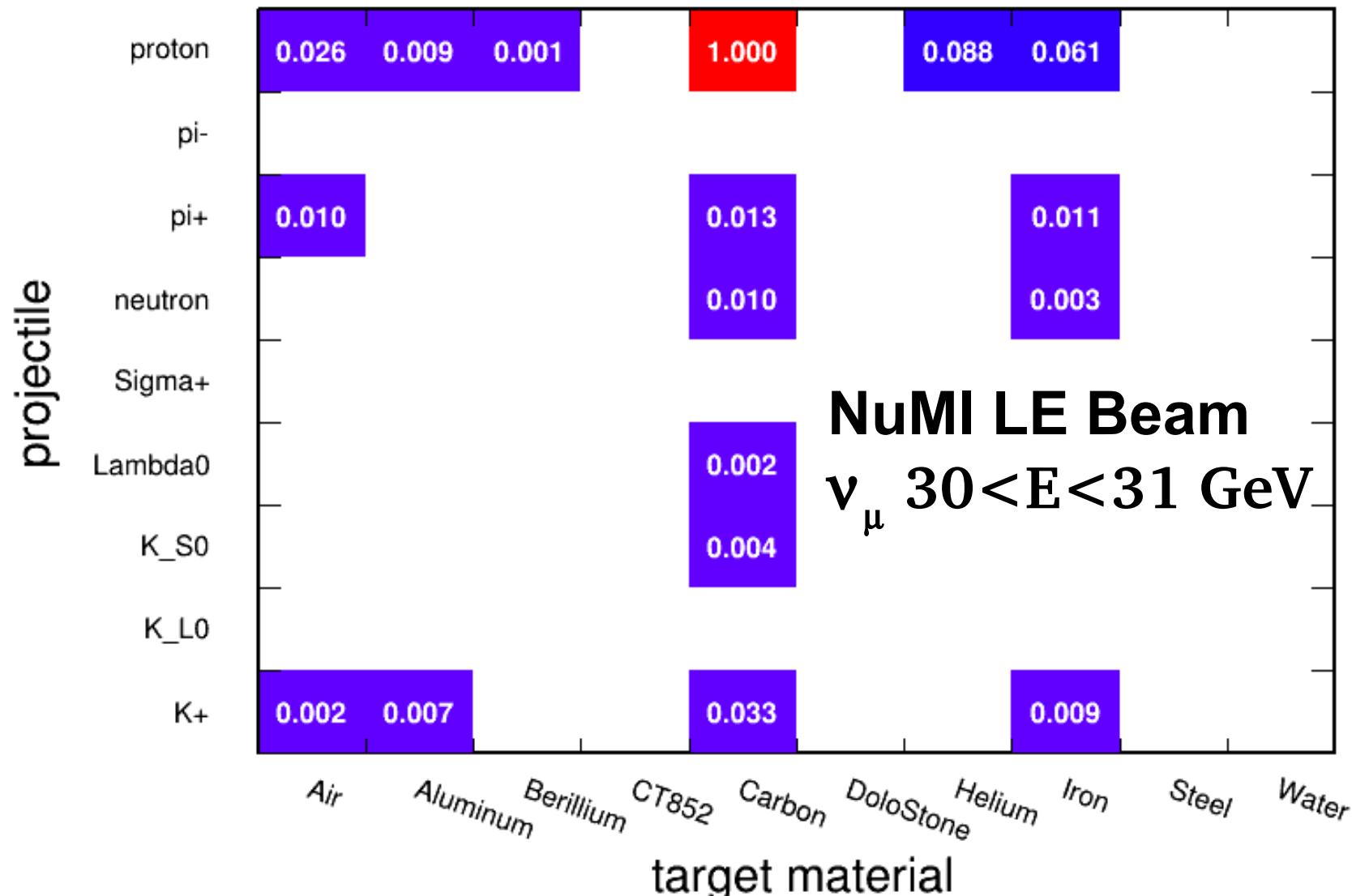


An interaction map

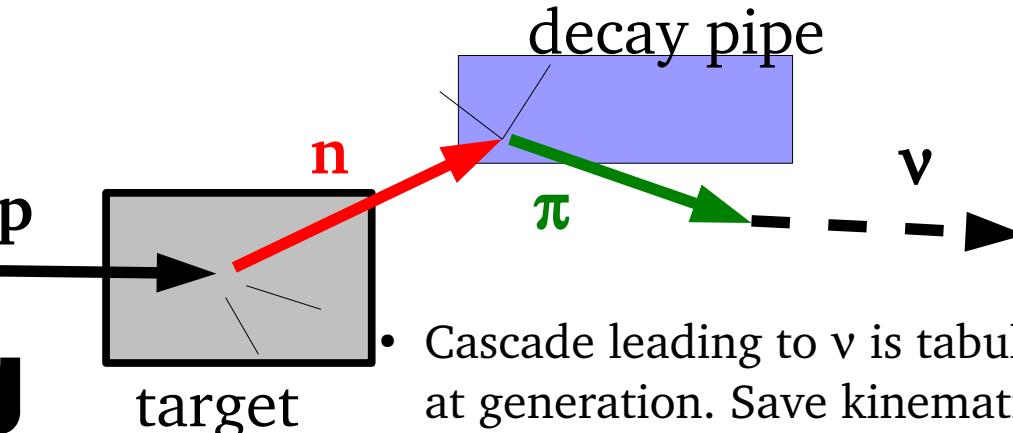


An interaction map

Interactions per event



Hadron Production Reweighting



- Cascade leading to ν is tabulated at generation. Save kinematics & material
- In analysis, interactions reweighted as $\sigma(\text{data})/\sigma(\text{MC})$
- Includes correction for beam attenuation in the target.

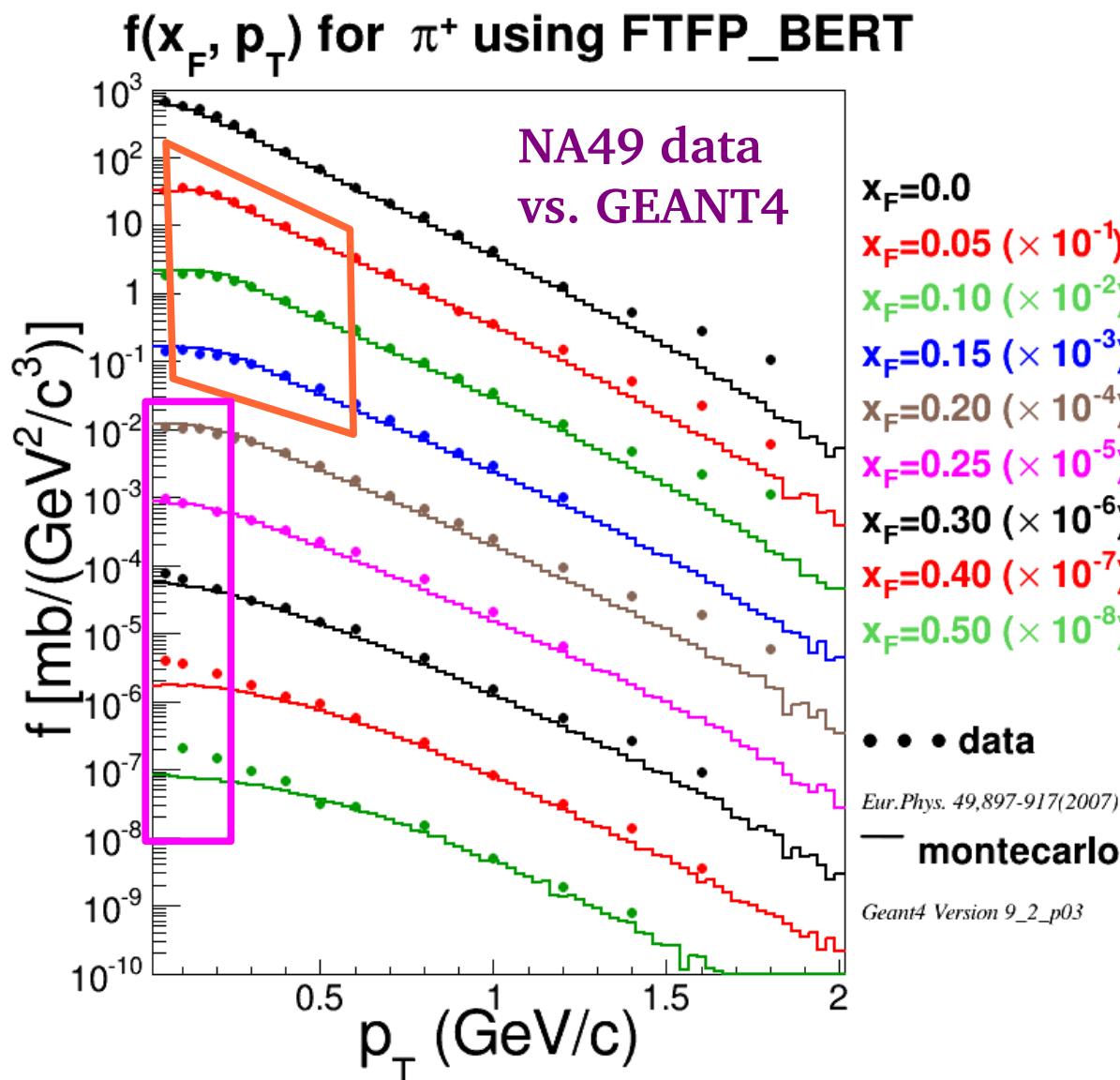
Datasets Used

- NA49 pC @ 158 GeV
 - π^\pm production for $xF < 0.5$ [*Eur.Phys.J. C49 (2007) 897*]
 - K^\pm production for $xF < 0.2$ [*G. Tinti Ph.D. thesis*]
 - p production for $xF < 0.9$ [*Eur.Phys.J. C73 (2013) 2364*]
- MIPP pC @ 120 GeV [*A. Lebedev Ph.D. thesis*]
 - K/π ratio + NA49 extends kaon coverage to $xF < 0.5$
 - Weights applied for $12 < p_{\text{incident}} < 120$ GeV.
 - Data cross-section scaled using FLUKA [www.fluka.org]
 - Checked by comparing to NA61 pC $\rightarrow \pi^\pm X$ at 31 GeV/c [*Phys.Rev. C84 (2011) 034604*]
 - Interactions on Al, Fe, He and Air treated as if on C

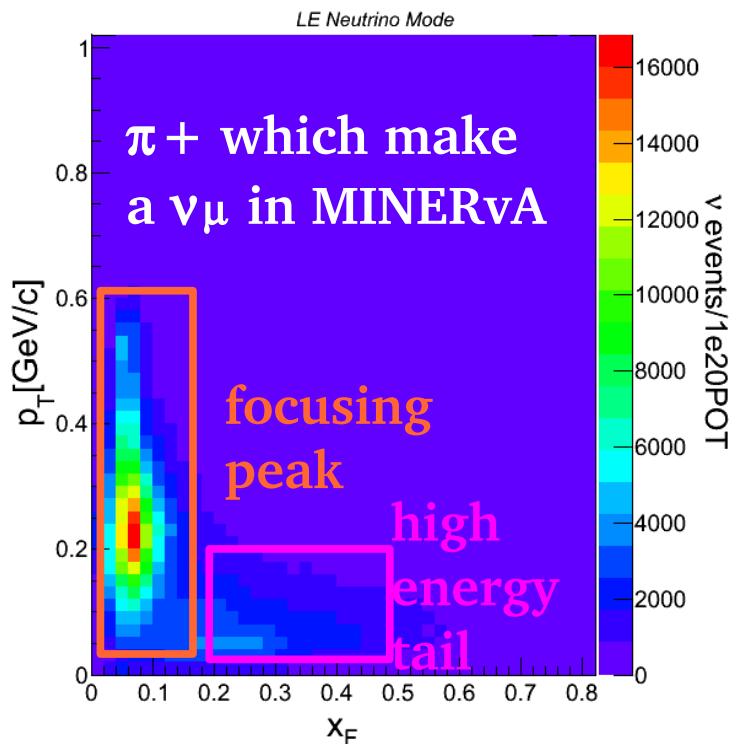
} some p_T dependence

NA49: pC $\rightarrow \pi, K, p, n$ @ 158 GeV

$f(x_F, p_T) = E d^3\sigma/dp^3$ = invariant production cross-section

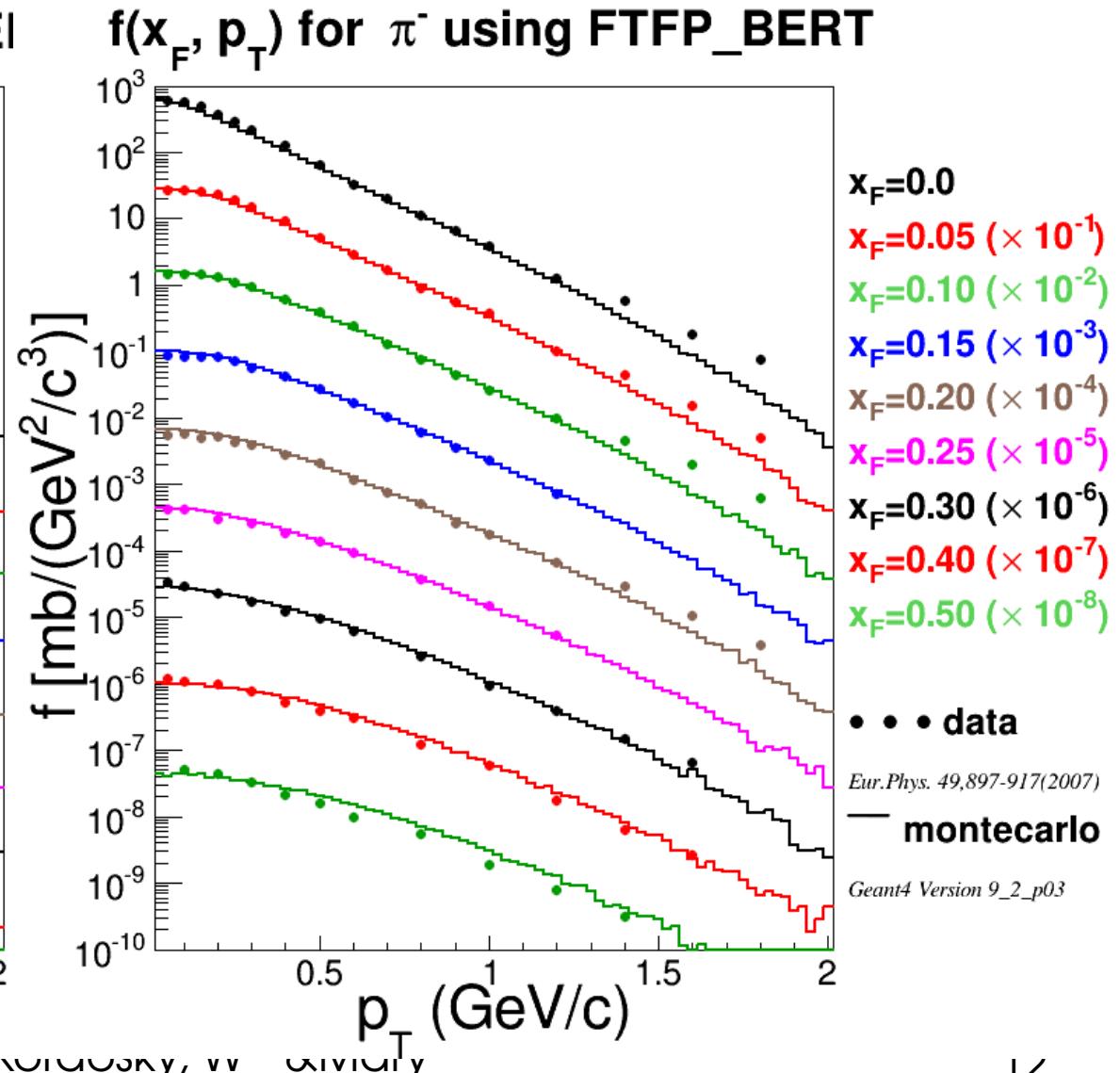
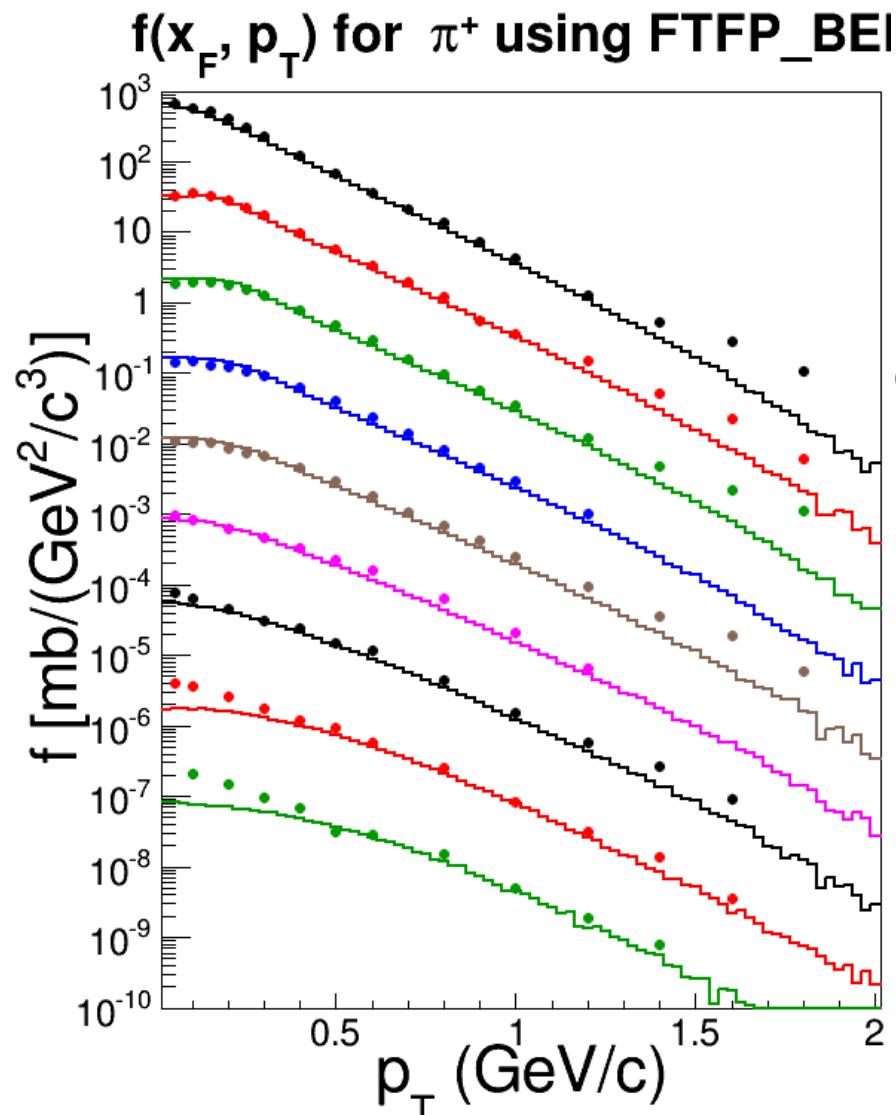


Transverse Momentum vs Feynman x for π^+



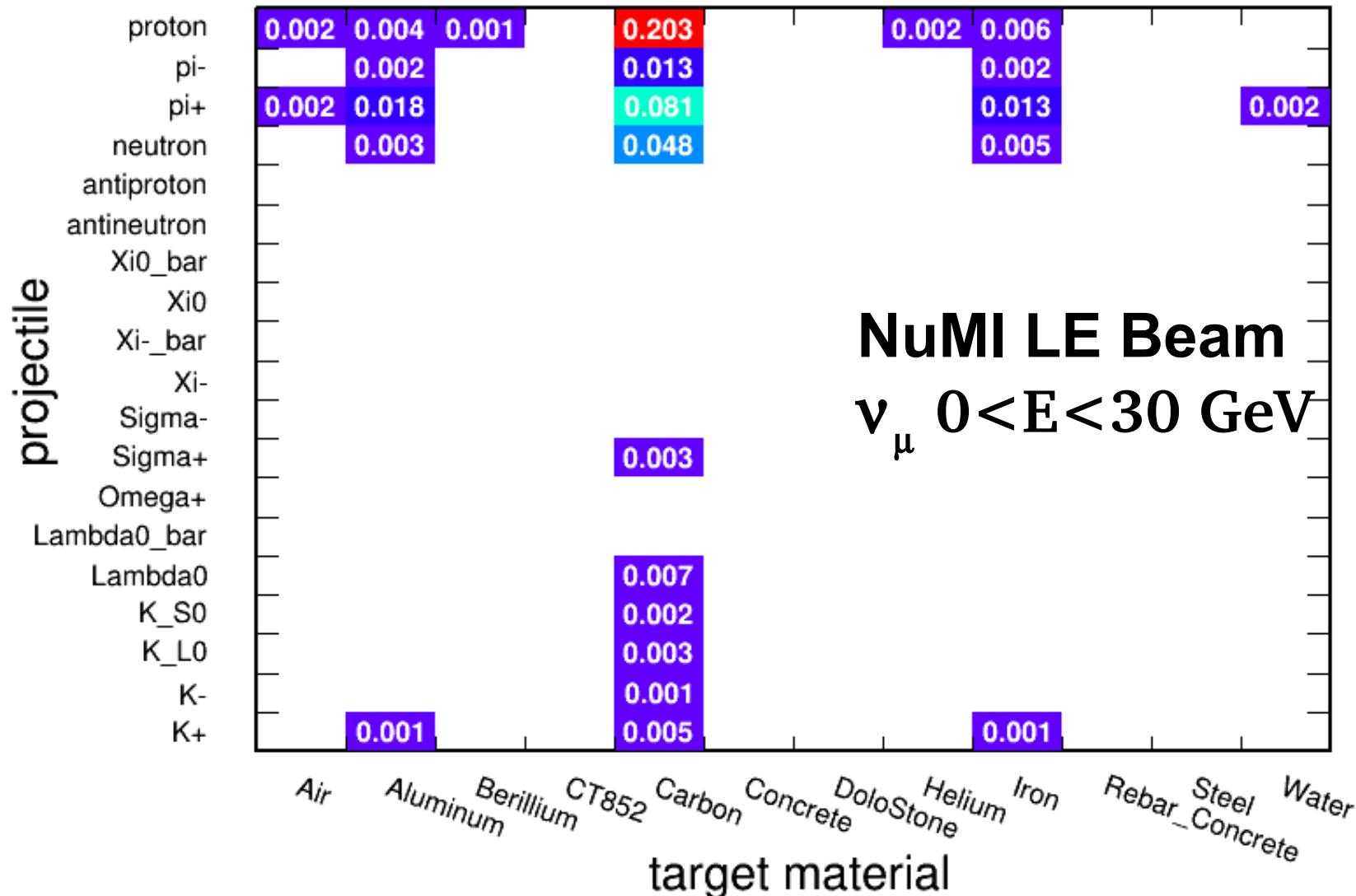
Uncertainties
7.5% systematic
2-10% statistical

NA49 Data vs MC



An interaction map

Interactions per event **unconstrained** by HP data



Q: How much reweighting do we do?

A: We constrain about 70% of interactions

neutrino energy	average # interactions / event	% interactions reweighted
3-4 GeV	1.362	75.18%
15-16 GeV	1.303	71.93%
30-31 GeV	1.30	64.0%
0-30 GeV	1.463	69.62%

What are we missing?

ν_μ $0 < E < 30 \text{ GeV}$

Total interactions / event = 1.463

- For incident protons

interactions / event

possible to address

produced particle	unconstrained	all
p	0.108	0.236
π^\pm	0.015	0.877
K^\pm	0.002	0.031
$K_s K_L$	0.028	0.028
n	0.049	0.049

- Other incident particles

possible to address

incident particle	interactions/event
π^\pm	0.134
n	0.057
$K^\pm, K_s K_L$	0.018
all others	0.013

What are we missing?

ν_μ $3 < E < 4 \text{ GeV}$

Total interactions / event = 1.362

- For incident protons

interactions / event

possible to address

produced particle	unconstrained	all
p	0.082	0.187
π^\pm	0.005	0.916
K^\pm	0.002	0.009
$K_s K_L$	0.026	0.026
n	0.039	0.039

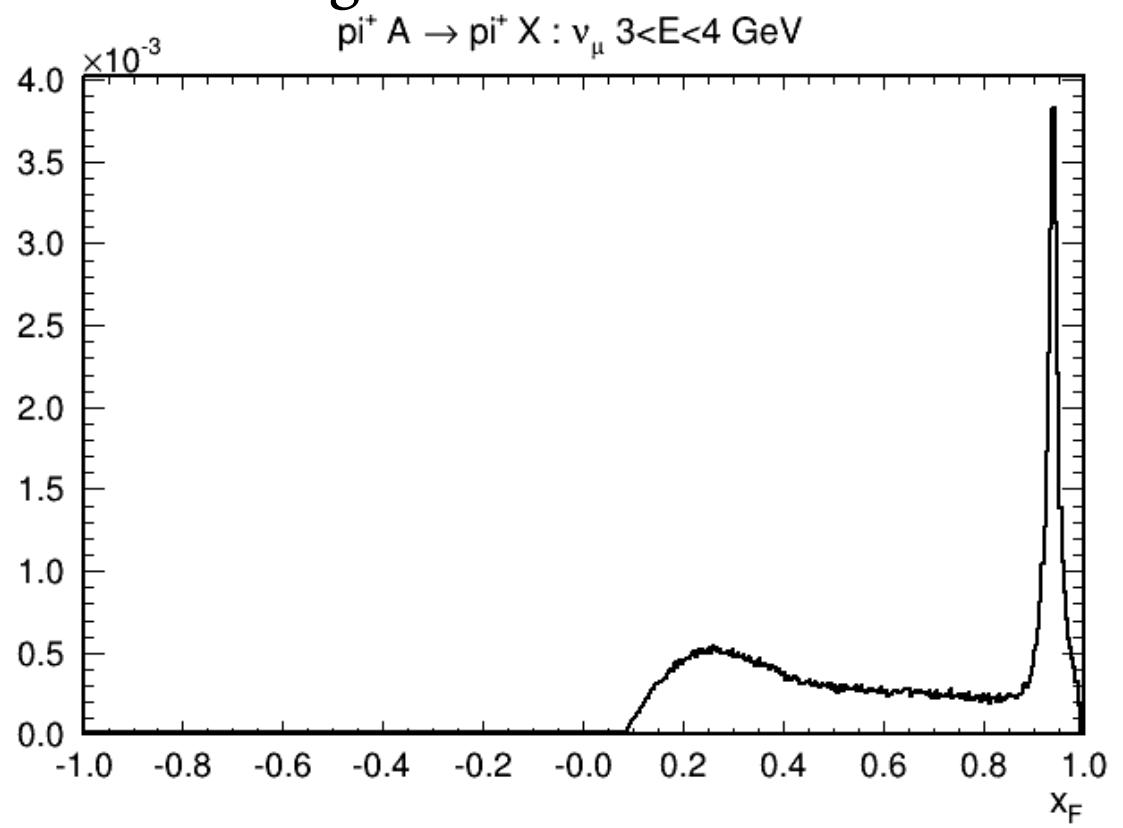
- Other incident particles

possible to address

incident particle	interactions/event
π^\pm	0.108
n	0.043
$K^\pm, K_s K_L$	0.011
all others	0.012

Notes on π, n, K incident: 3-4 GeV

- For incident π^+ , the overwhelming number of interactions in our history chain are ones in which another π^+ is made. This includes a significant energy degradation.



- For other particles, the overwhelming number of interactions also produce a π^+
- Almost always, carbon is the target material.

What are we missing?

v_μ $15 < E < 16 \text{ GeV}$

Total interactions / event = 1.303

- For incident protons

interactions / event

produced particle	unconstrained	all
p	0.135	0.186
π^\pm	0.069	0.668
K^\pm	0.008	0.292
$K_S K_L$	0.018	0.018
n	0.016	0.016

loss of coverage at $x_F > 0.5$

possible to address

- Other incident particles

incident particle	interactions/event
π^\pm	0.062
n	0.019
$K^\pm, K_S K_L$	0.031
all others	0.004

possible to address

What are we missing?

v_μ $30 < E < 31 \text{ GeV}$

Total interactions / event = 1.30

- For incident protons

interactions / event

produced particle	unconstrained	all
p	0.14	0.19
π^\pm	0.14	0.15
K^\pm	0.05	0.83
$K_s K_L$	0.01	0.01
n	0.01	0.01

loss of coverage at $x_F > 0.5$

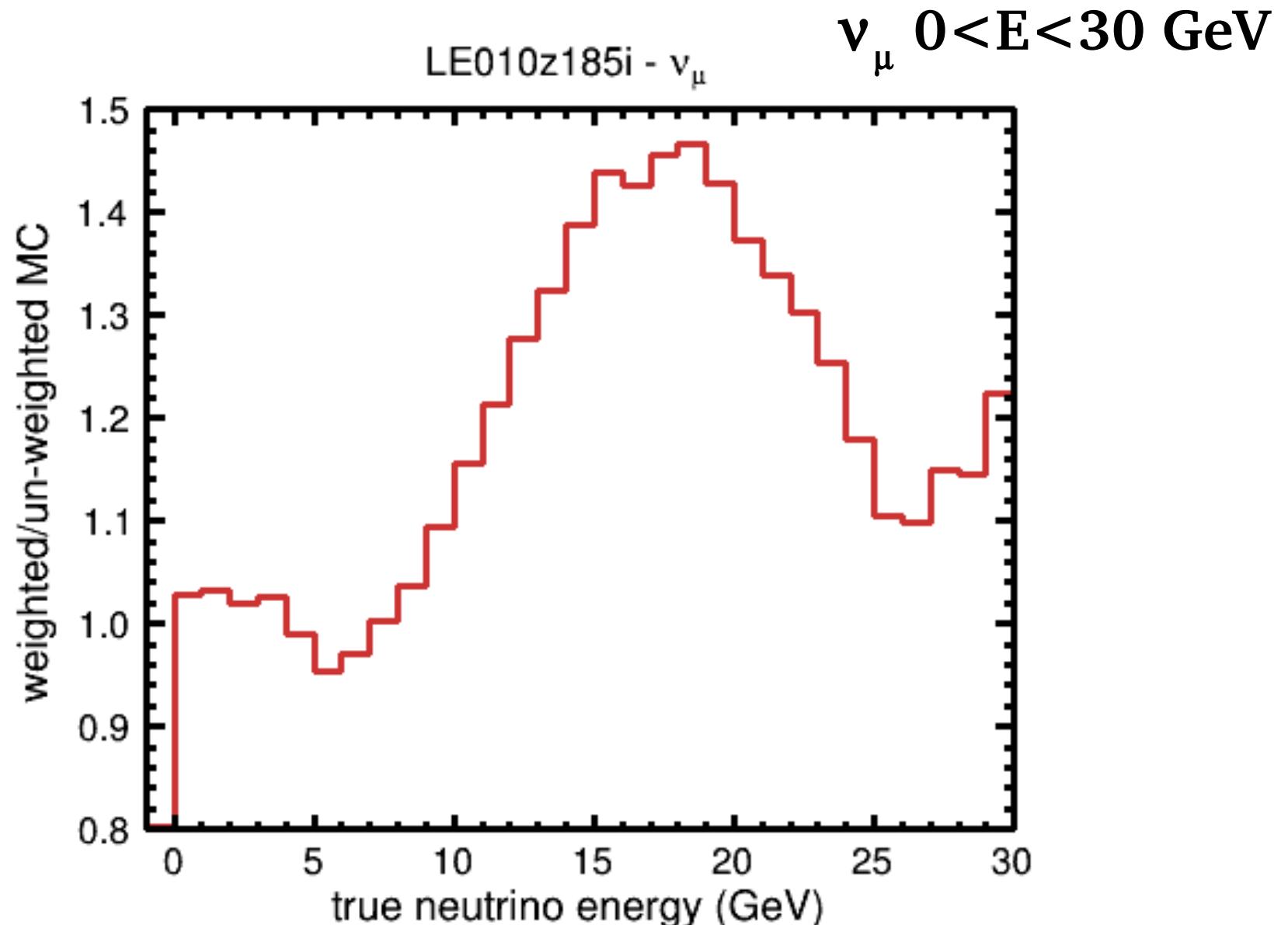
possible to address

- Other incident particles

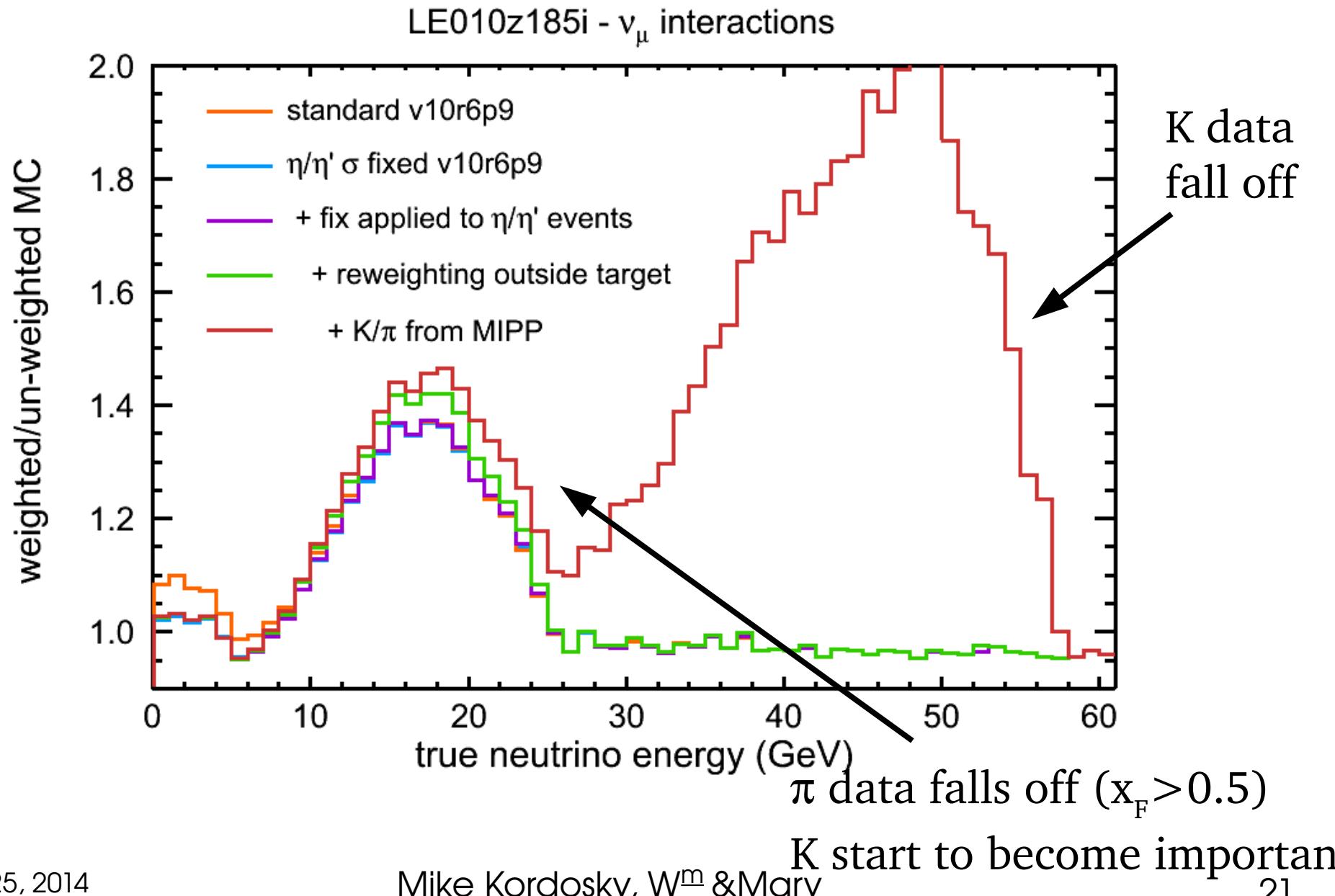
incident particle	interactions/event
π^\pm	0.04
n	0.01
$K^\pm, K_s K_L$	0.06
all others	<0.01

possible to address

Effect of reweighting on the flux



Reweighting components



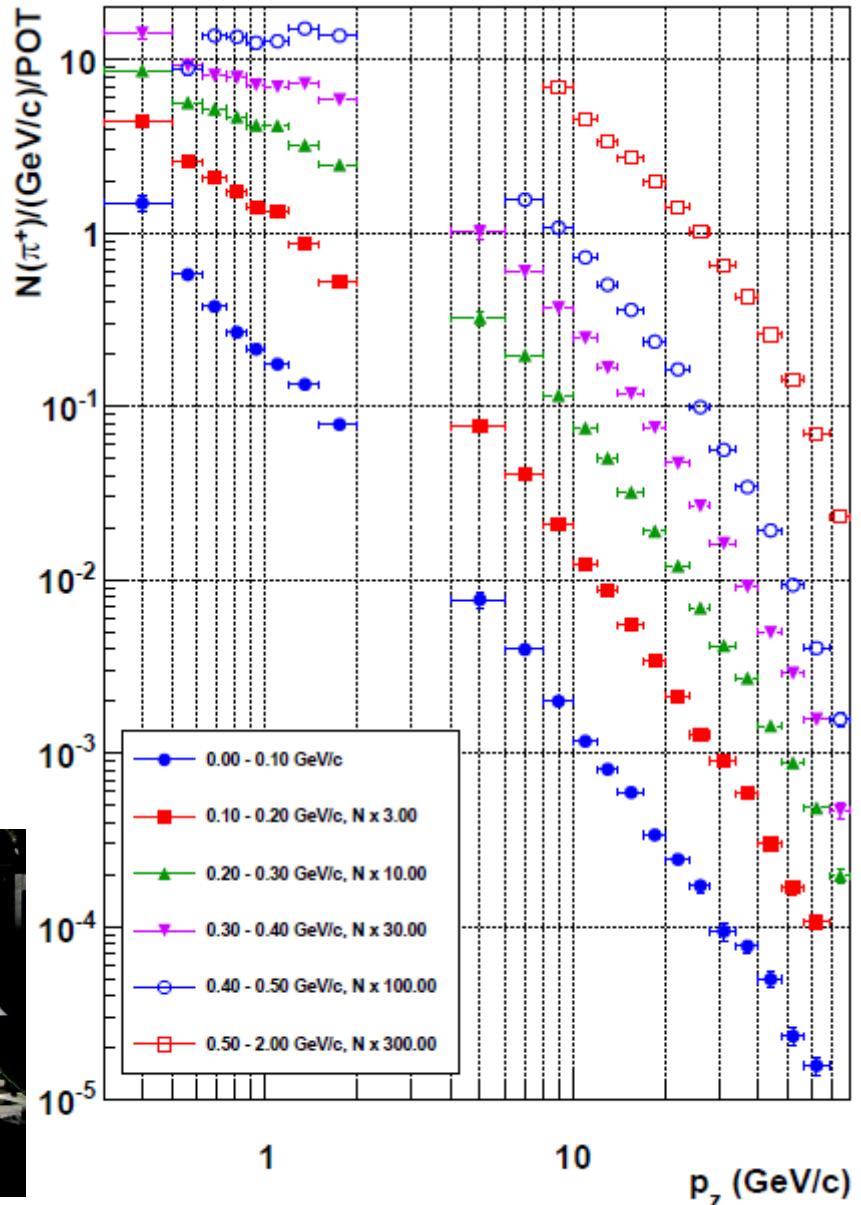
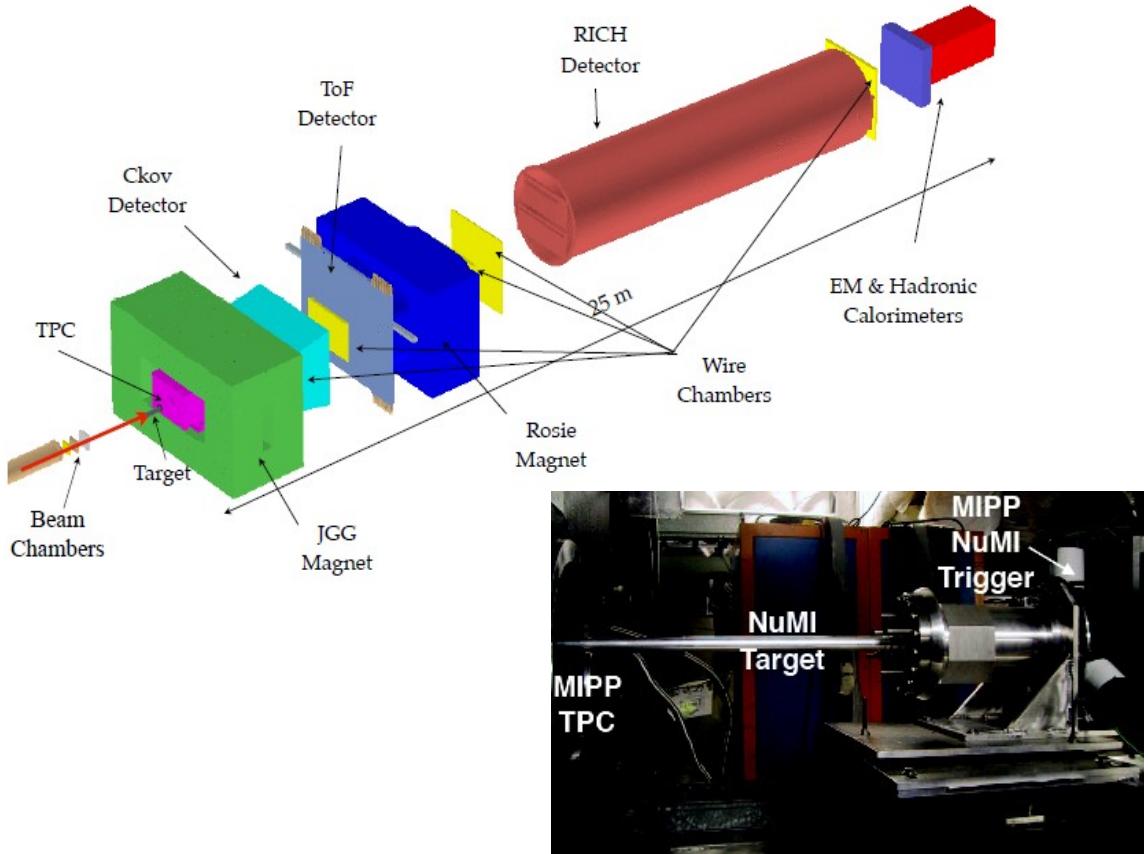
MIPP NuMI target data

Measurement of Charged Pion Production Yields off the NuMI Target

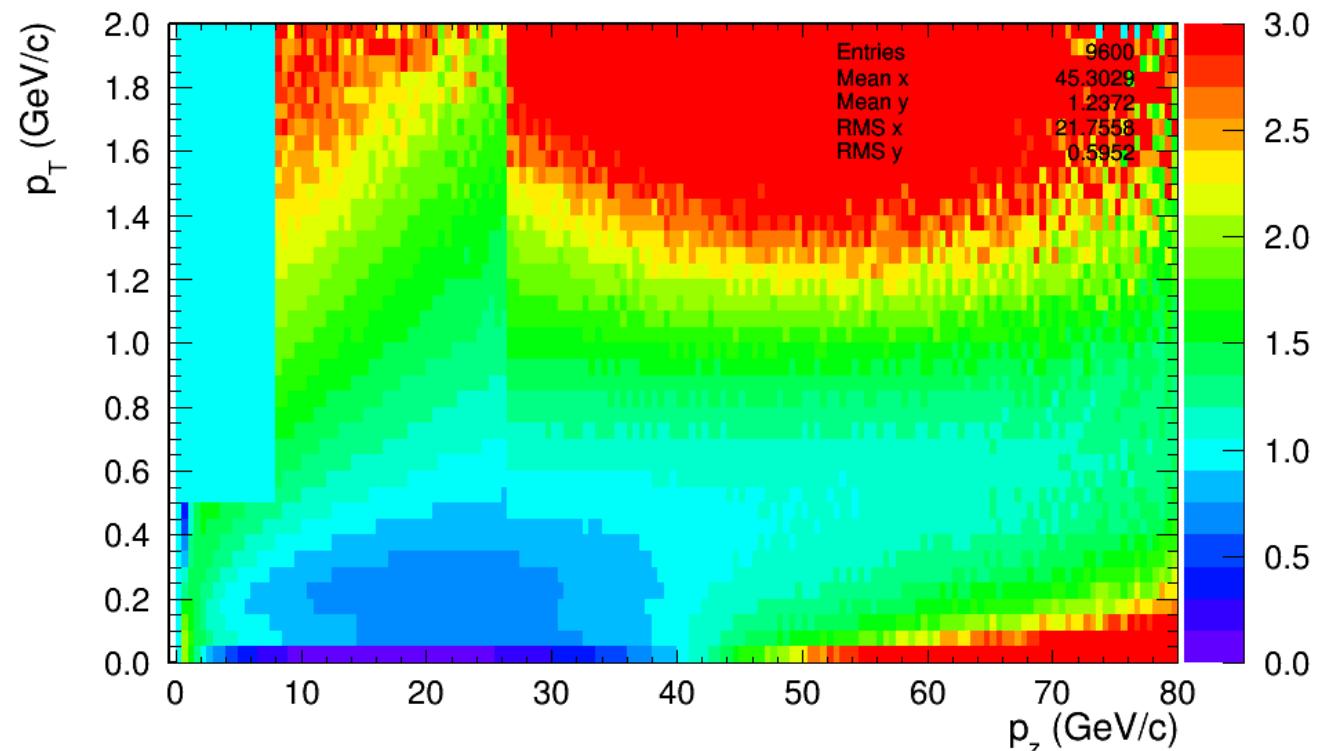
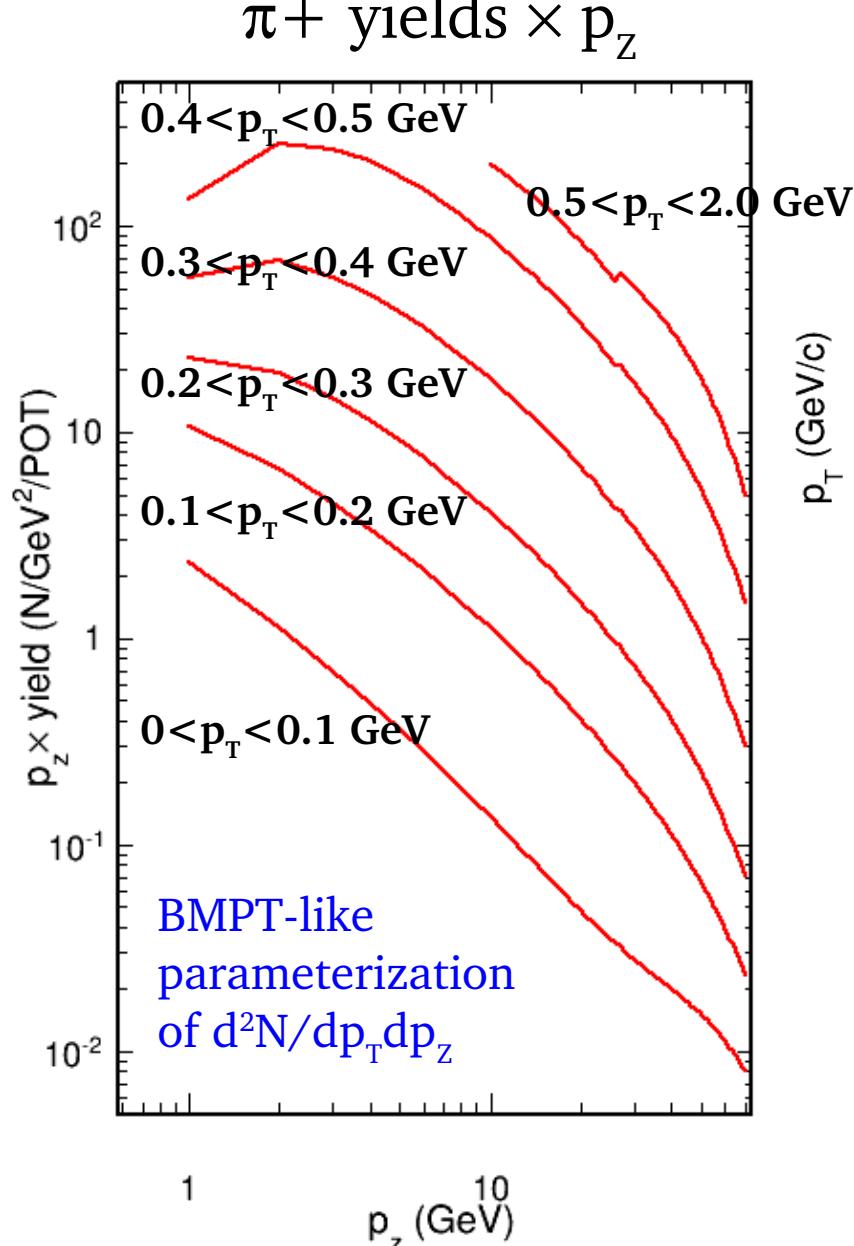
J. M. Paley,¹ M. D. Messier,⁹ R. Raja,^{6,*} U. Akgun,^{10,2} D. M. Asner,^{11,†} G. Aydin,^{10,‡} W. Baker,⁶
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 G. J. Feldman,⁷ A. Godley,¹⁶ N. Graf,^{9,§} J. Gronberg,¹¹ E. Gülmез,^{10,¶} Y. O. Günaydin,^{10,**}
 H. R. Gustafson,¹² E. P. Hartouni,¹¹ P. Hanlet,⁸ M. Heffner,¹¹ D. M. Kaplan,⁸ O. Kamaev,^{8,††} J. Klay,^{11,‡‡}
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 S. Mahajan,¹⁴ H. Meyer,¹⁸ D. E. Miller,¹⁵ S. R. Mishra,¹⁶ K. Nelson,¹⁷ T. Nigmanov,^{12,§} A. Norman,^{6,17}
 Y. Onel,¹⁰ A. Penzo,¹⁰ R. J. Peterson,³ D. Rajaram,^{8,12} D. Ratnikov,⁸ C. Rosenfeld,¹⁶ H. Rubin,⁸ S. Seun,⁷
 A. Singh,¹⁴ N. Solomey,¹⁸ R. A. Soltz,¹¹ Y. Torun,⁸ K. Wilson,¹⁶ D. M. Wright,¹¹ and Q. K. Wu¹⁶

(The MIPP Collaboration)

(Dated: April 24, 2014)



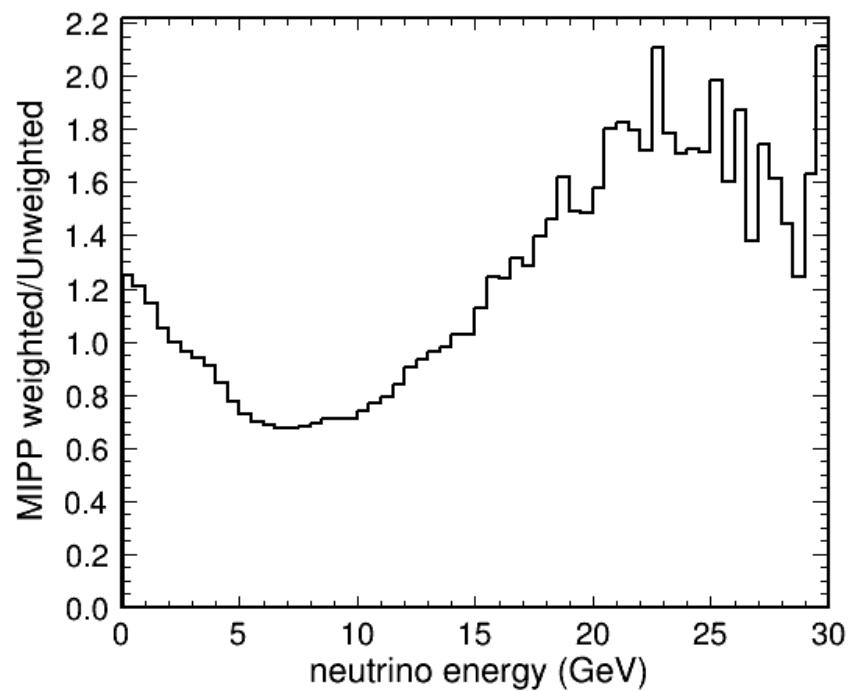
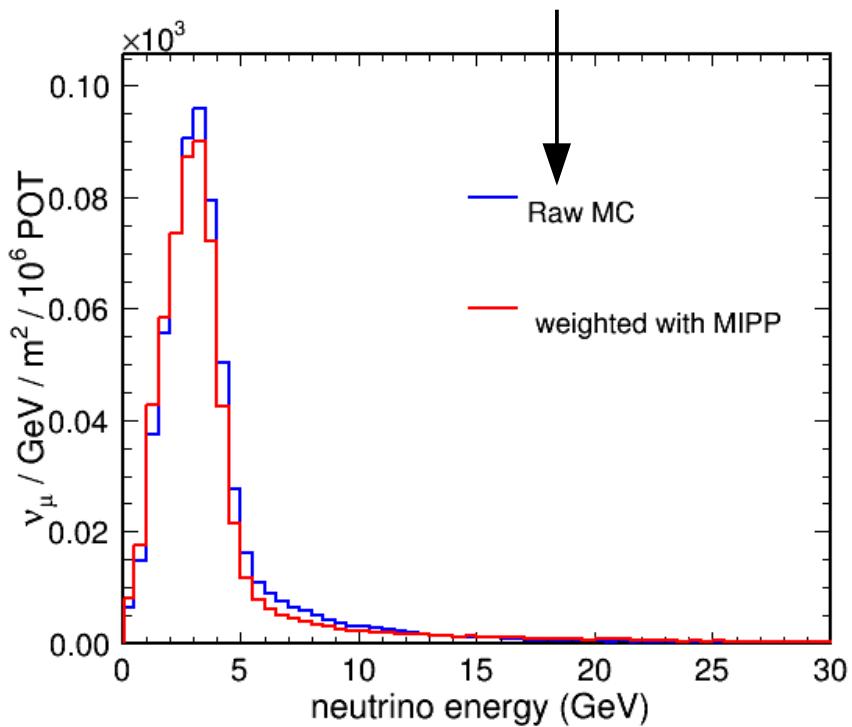
Parameterization



π^+ weights w.r.t. raw MINERvA MC
(FTFP G4_9_02_p3) as a function of p_T , p_z

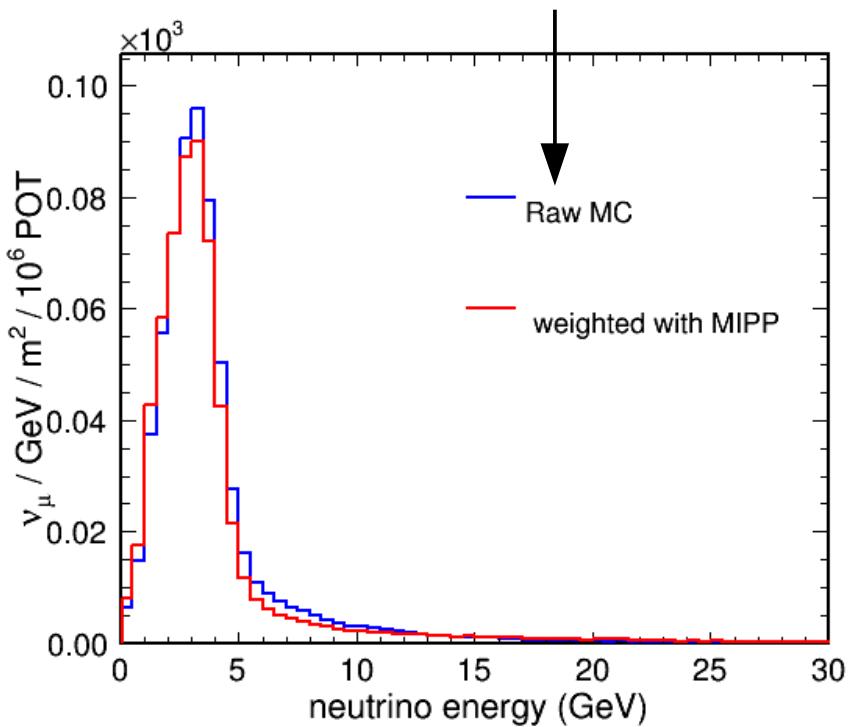
Results

MINERvA FTFP G4_9_02_p3

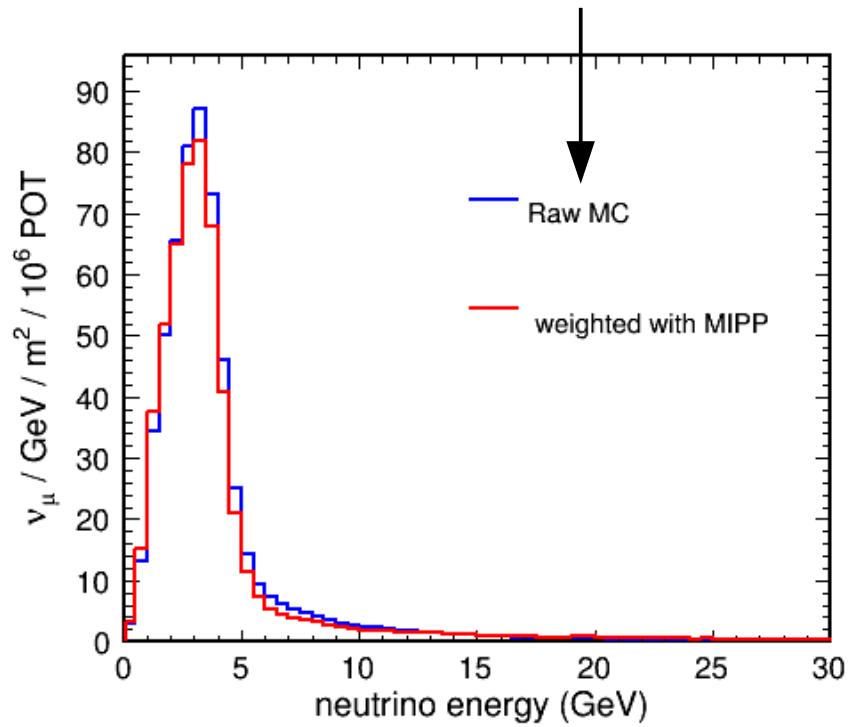


Results

MINERvA FTFP G4_9_02_p3

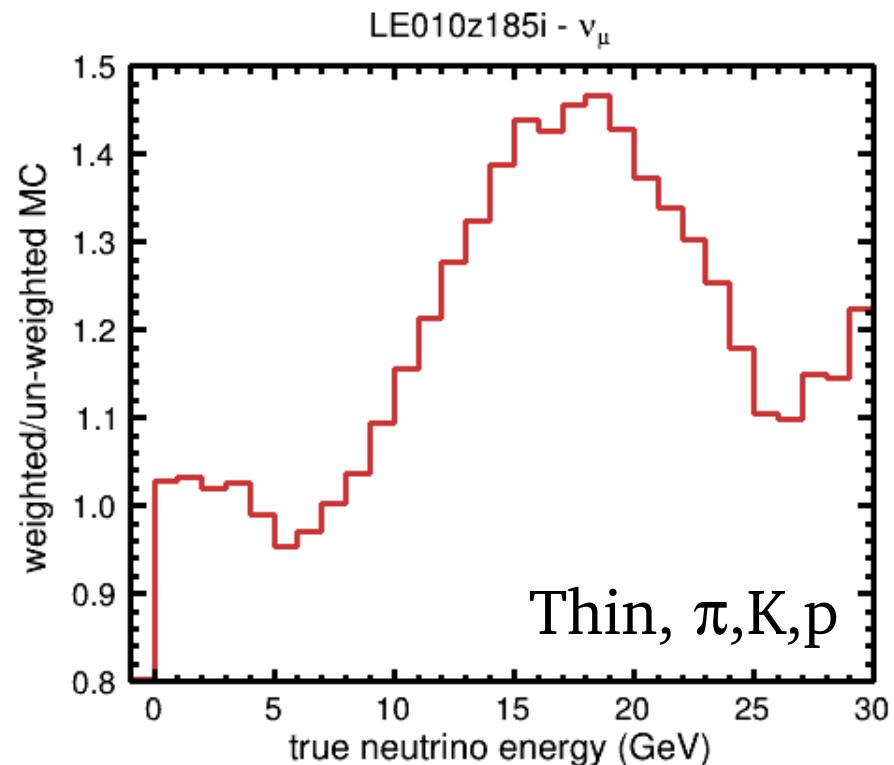
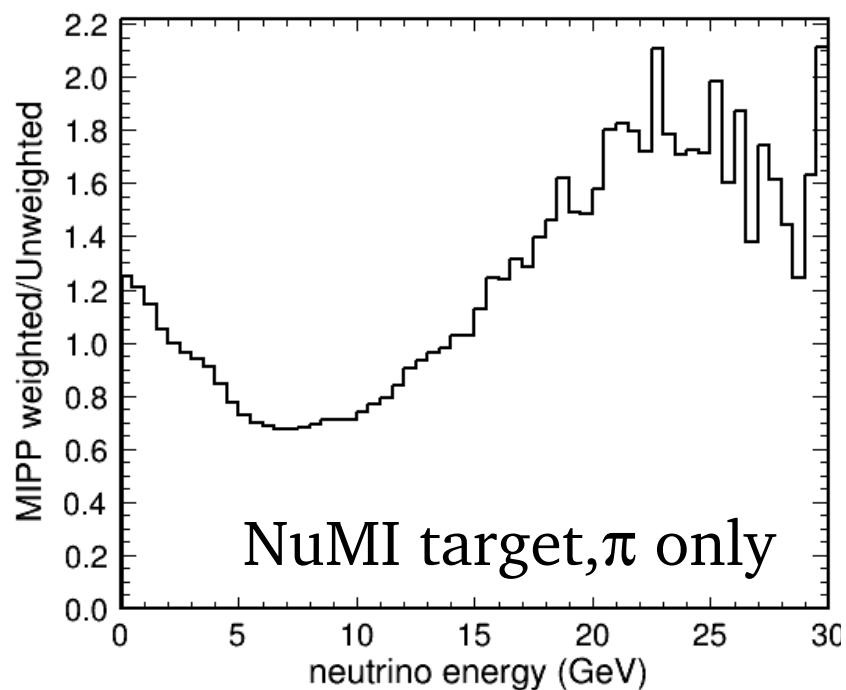


MINOS FLUGG (FLUKA08)



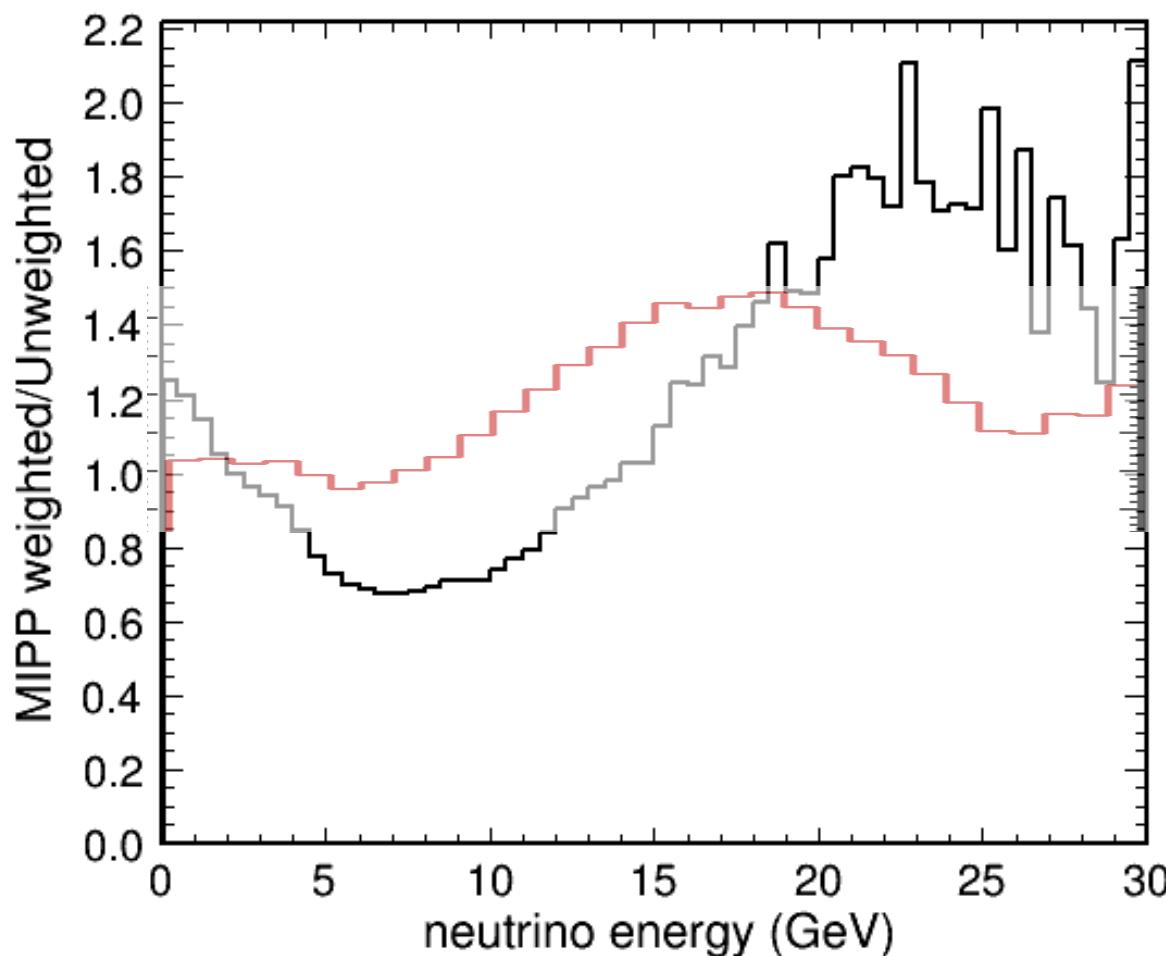
NuMI vs. thin target reweighting

MINERvA FTFP G4_9_02_p3



Thick vs. thin target reweighting

MINERvA FTFP G4_9_02_p3



- A “faculty” plot
- Interesting similarities but also surprisingly large differences
 - The behavior in the high energy tail could be quite consistent since the thin target data falls off there
 - Thick target: huge suppression of π^+ yield for $10 < p_z < 30$ GeV cause dip in $5 < E_\nu < 15$ GeV region
 - Much to understand here

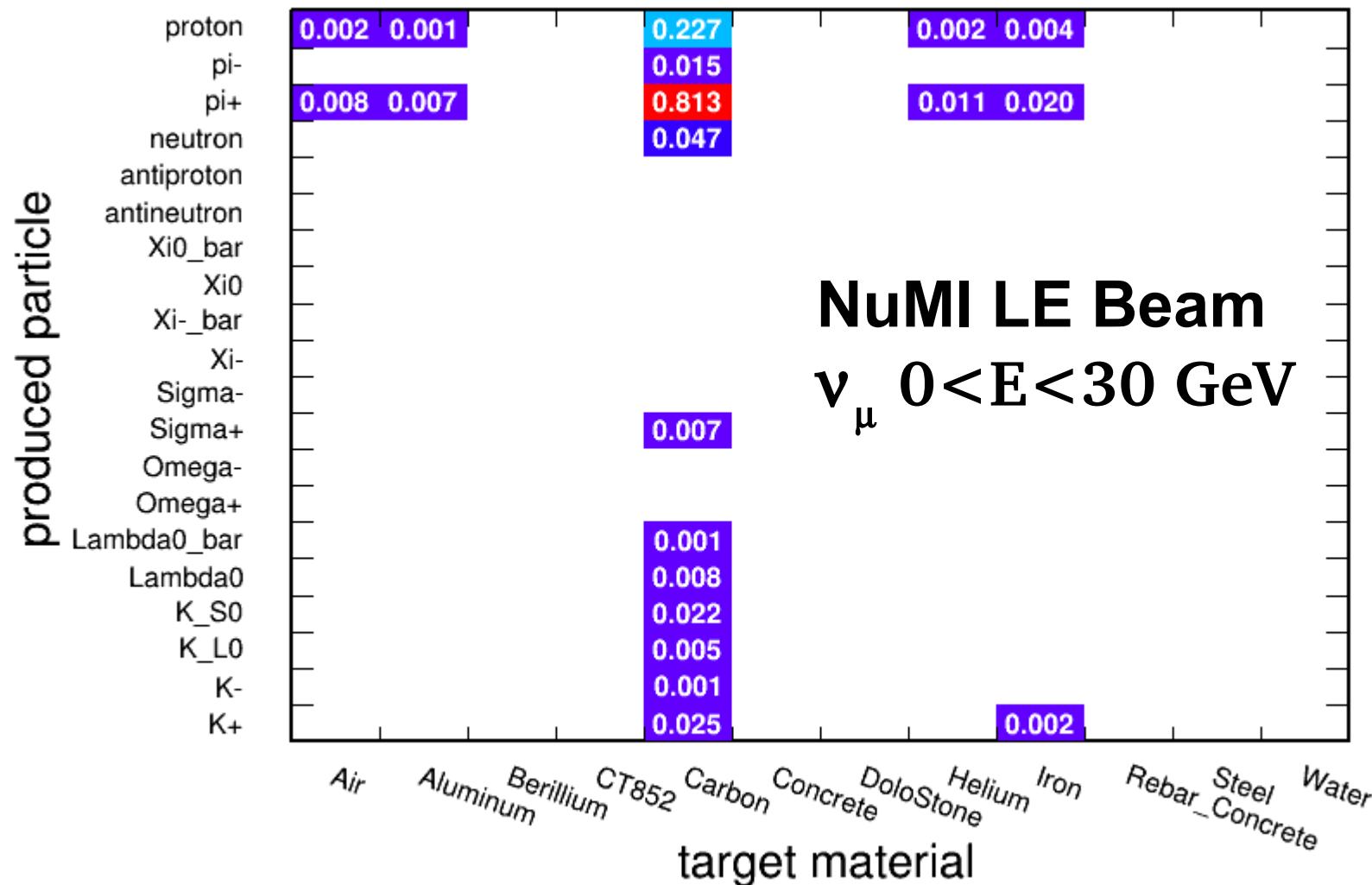
Discussion

- HP data are vital for understanding the flux from broad band beams
 - large collection of interactions characterized by projectile, target and produced particles
- pC data alone is not enough. At a minimum one also wants thin target π C data @ few 10s GeV. Other A also useful.
- Interaction reweighting requires a fastidious record of interaction chain leading to a neutrino
 - Design into beam simulation → NuMI-x format
- First look at NuMI target data
 - Big effect! Will take effort to understand.

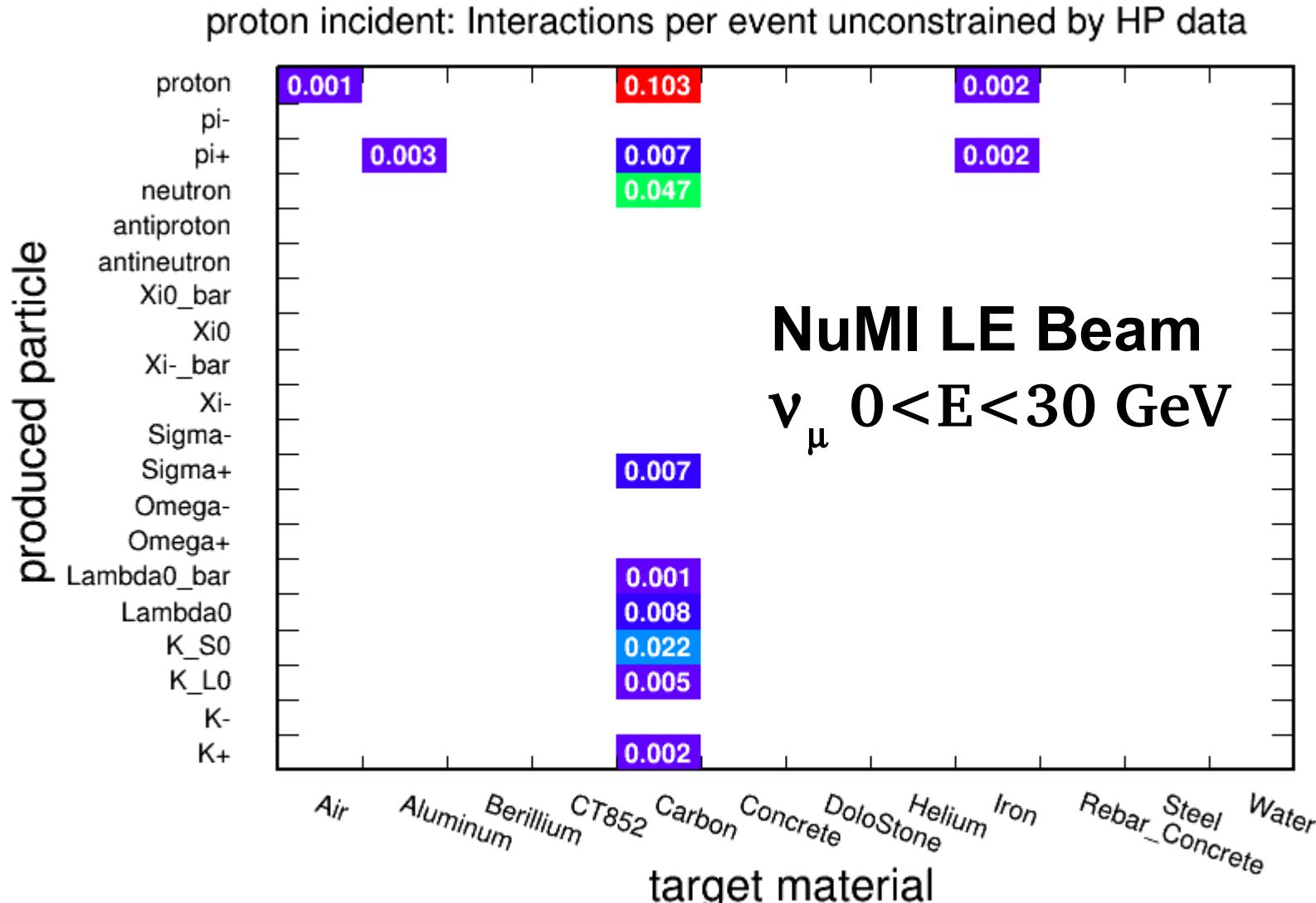
Backups

0-30 GeV

proton incident: Interactions per event

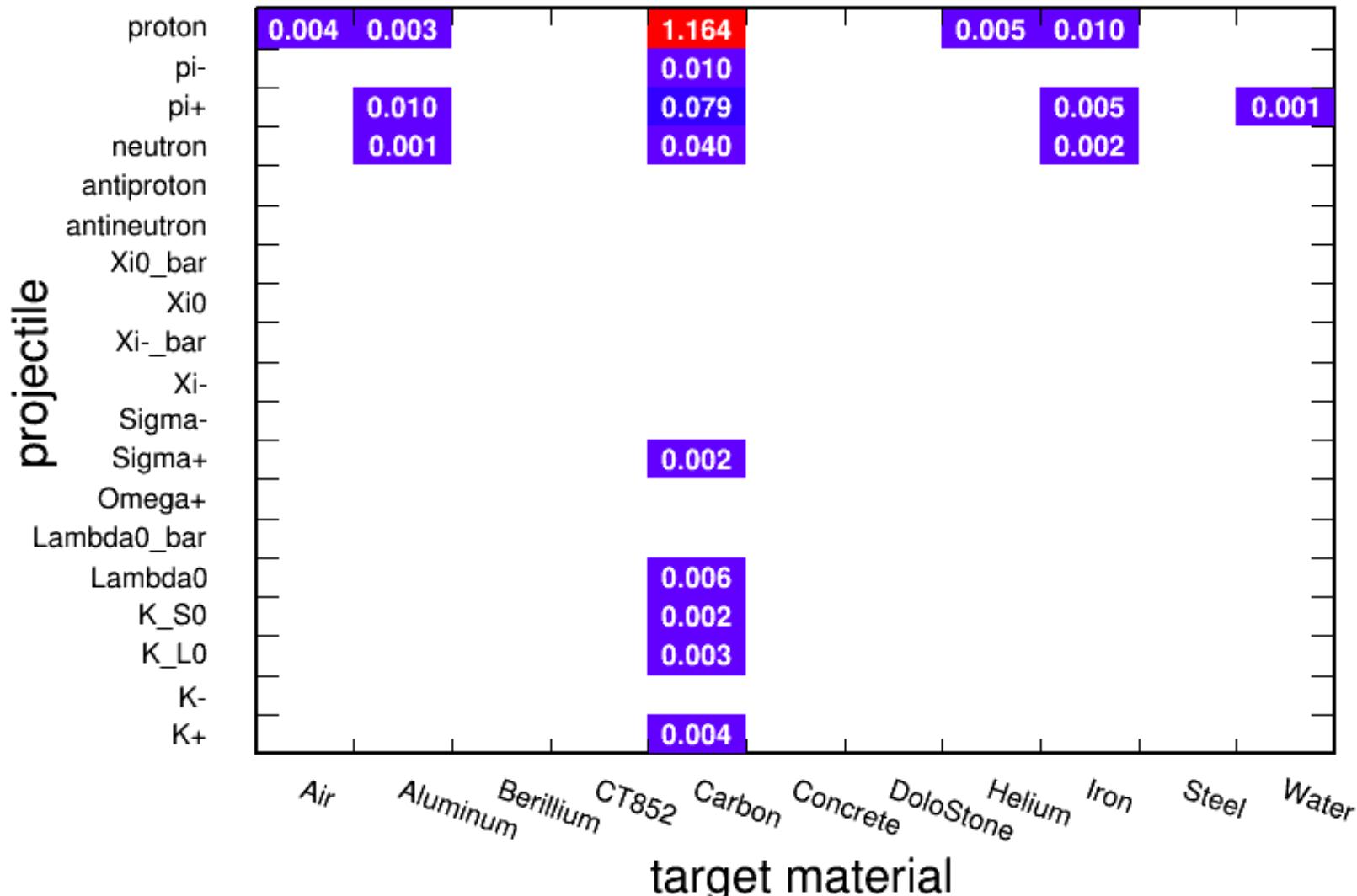


0-30 GeV



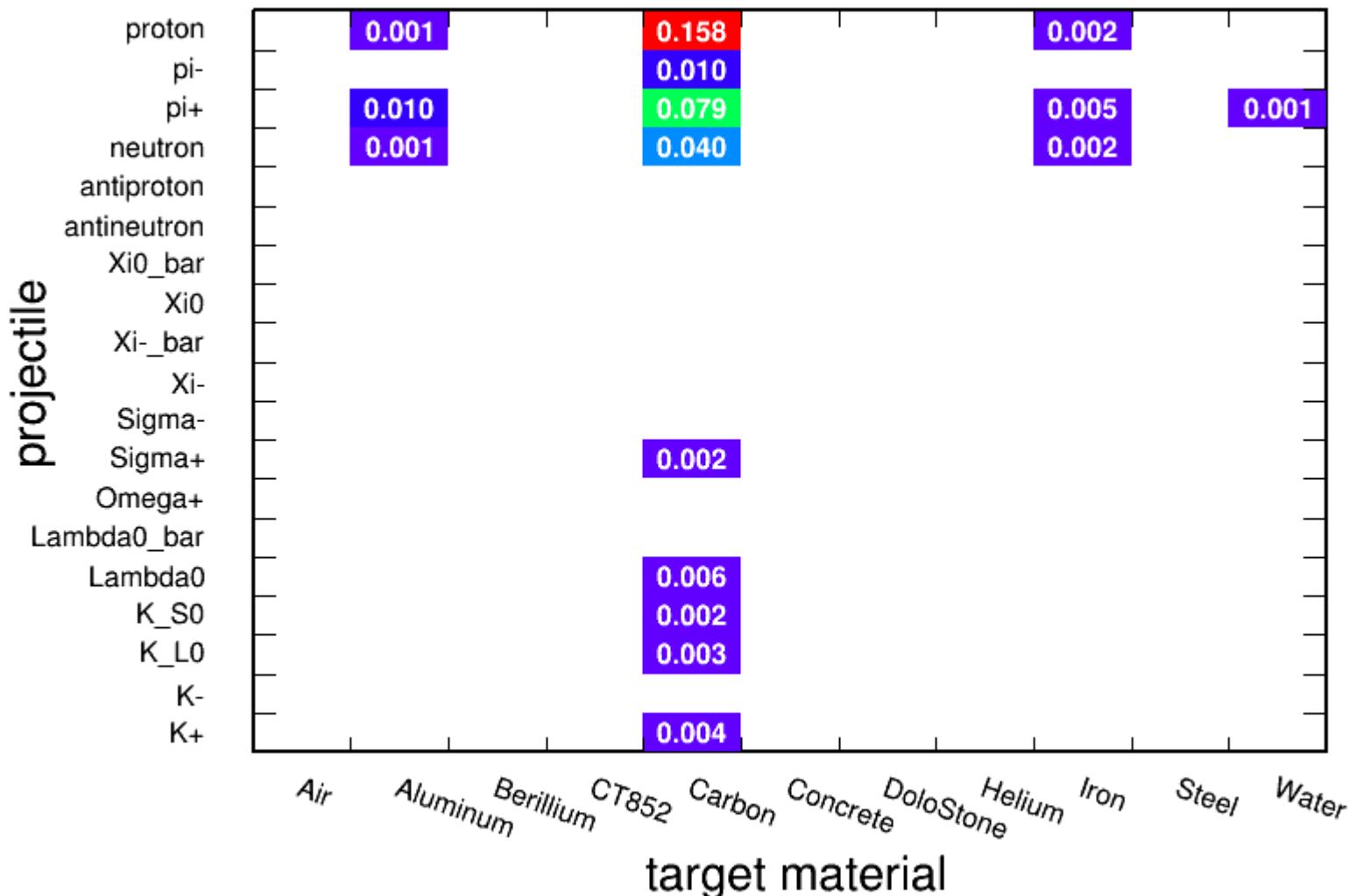
3-4 GeV

Interactions per event



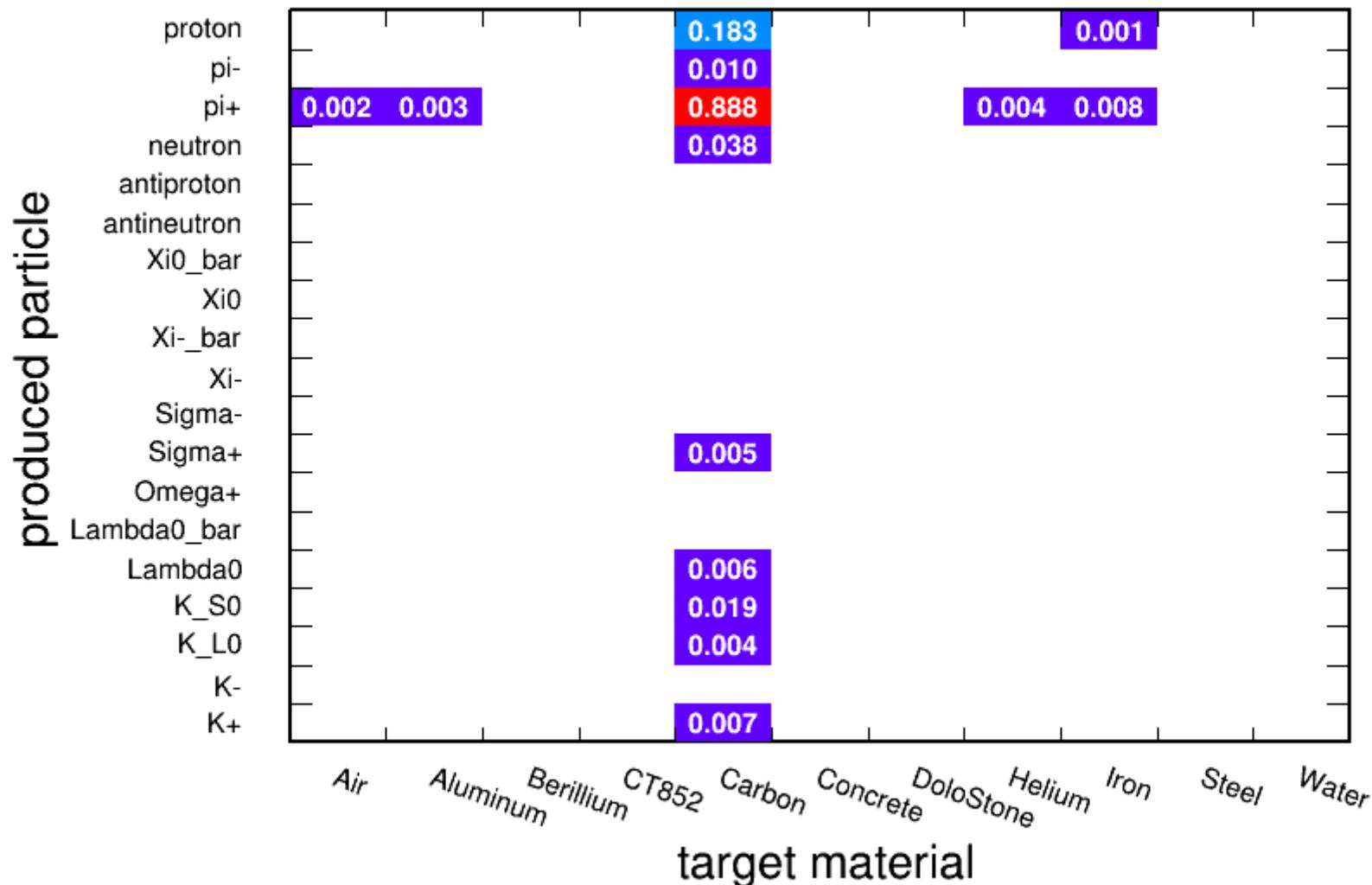
3-4 GeV

Interactions per event unconstrained by HP data



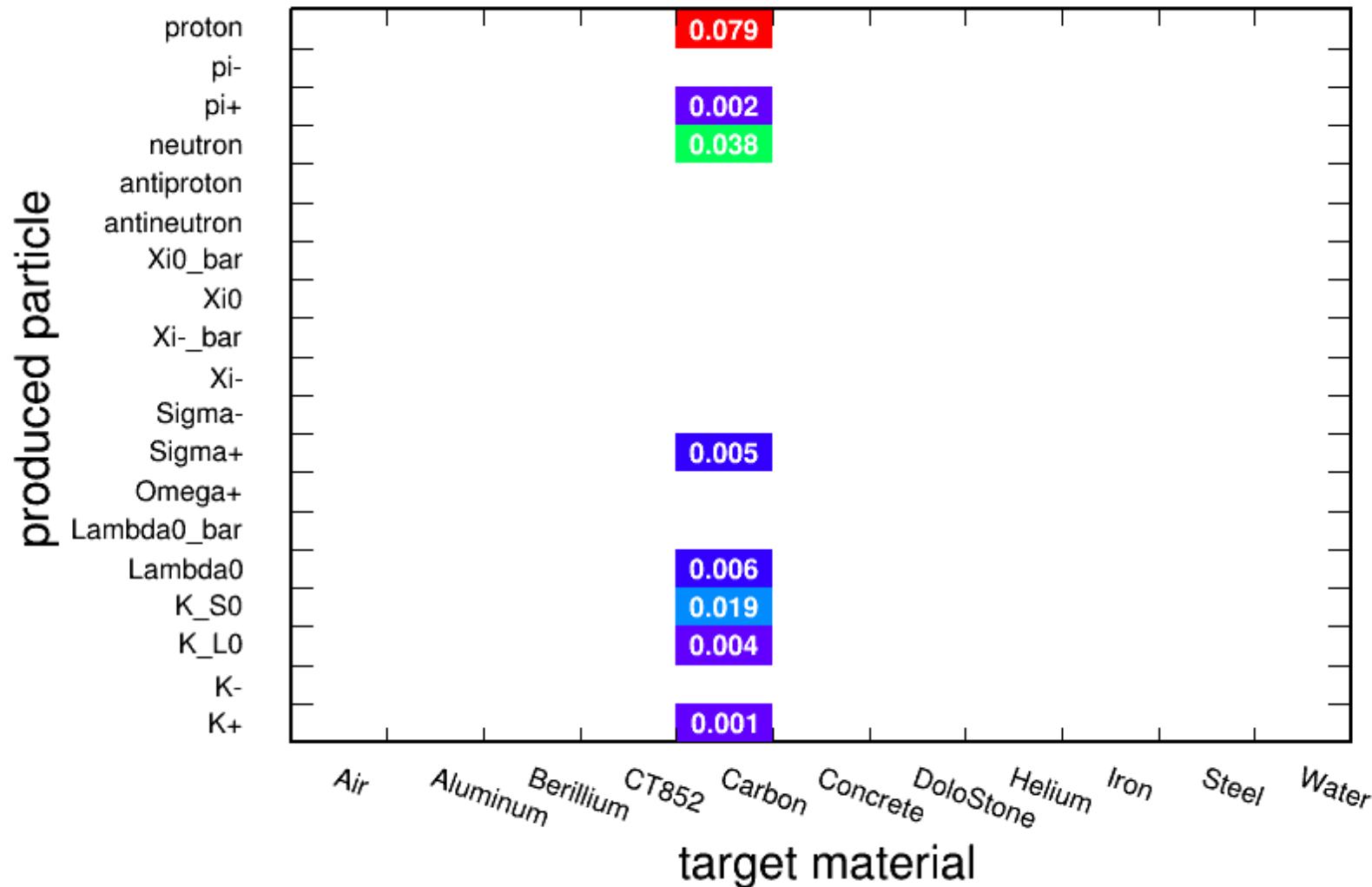
3-4 GeV: p A → X

proton incident: Interactions per event

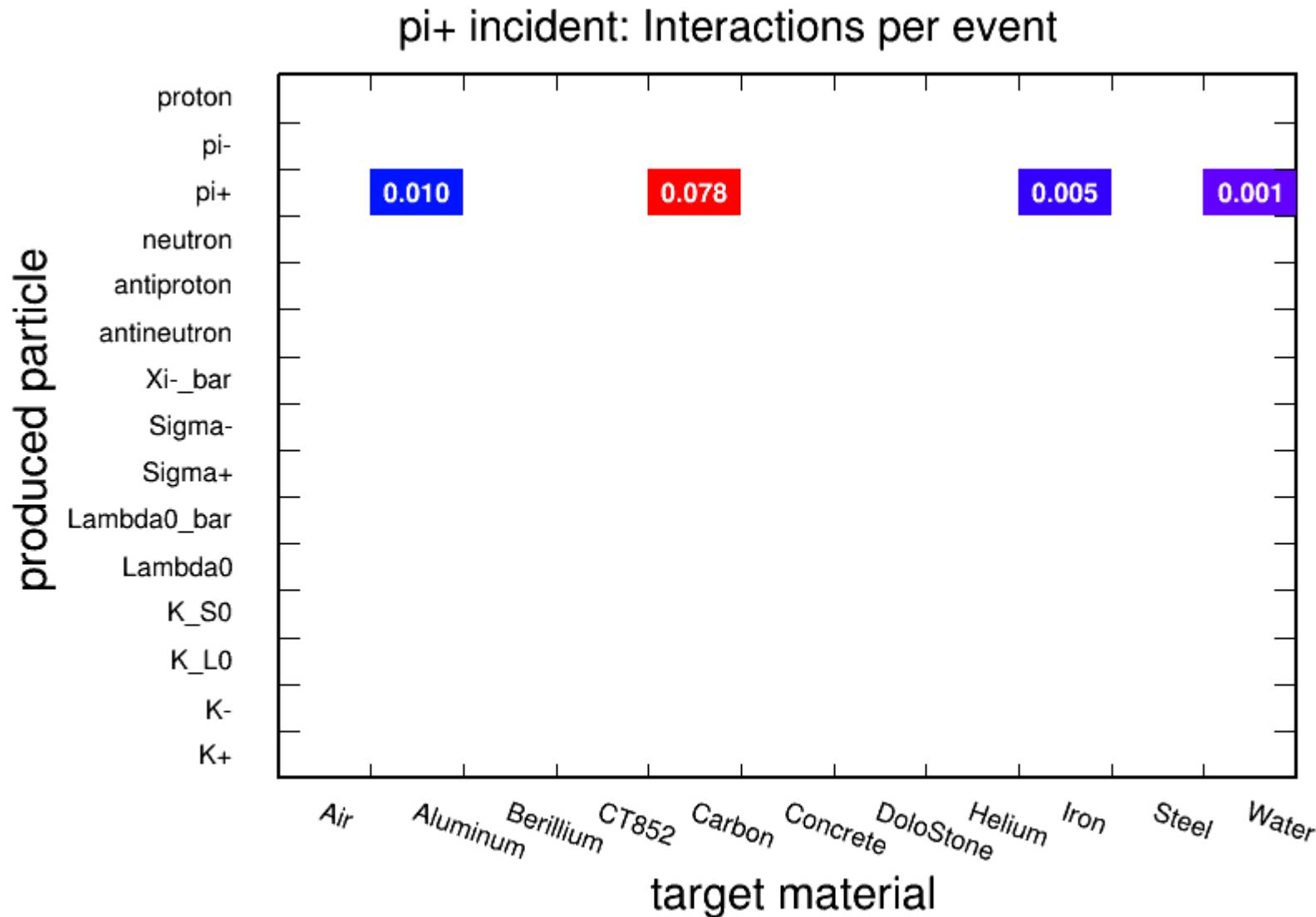


3-4 GeV: p A → X

proton incident: Interactions per event unconstrained by HP data

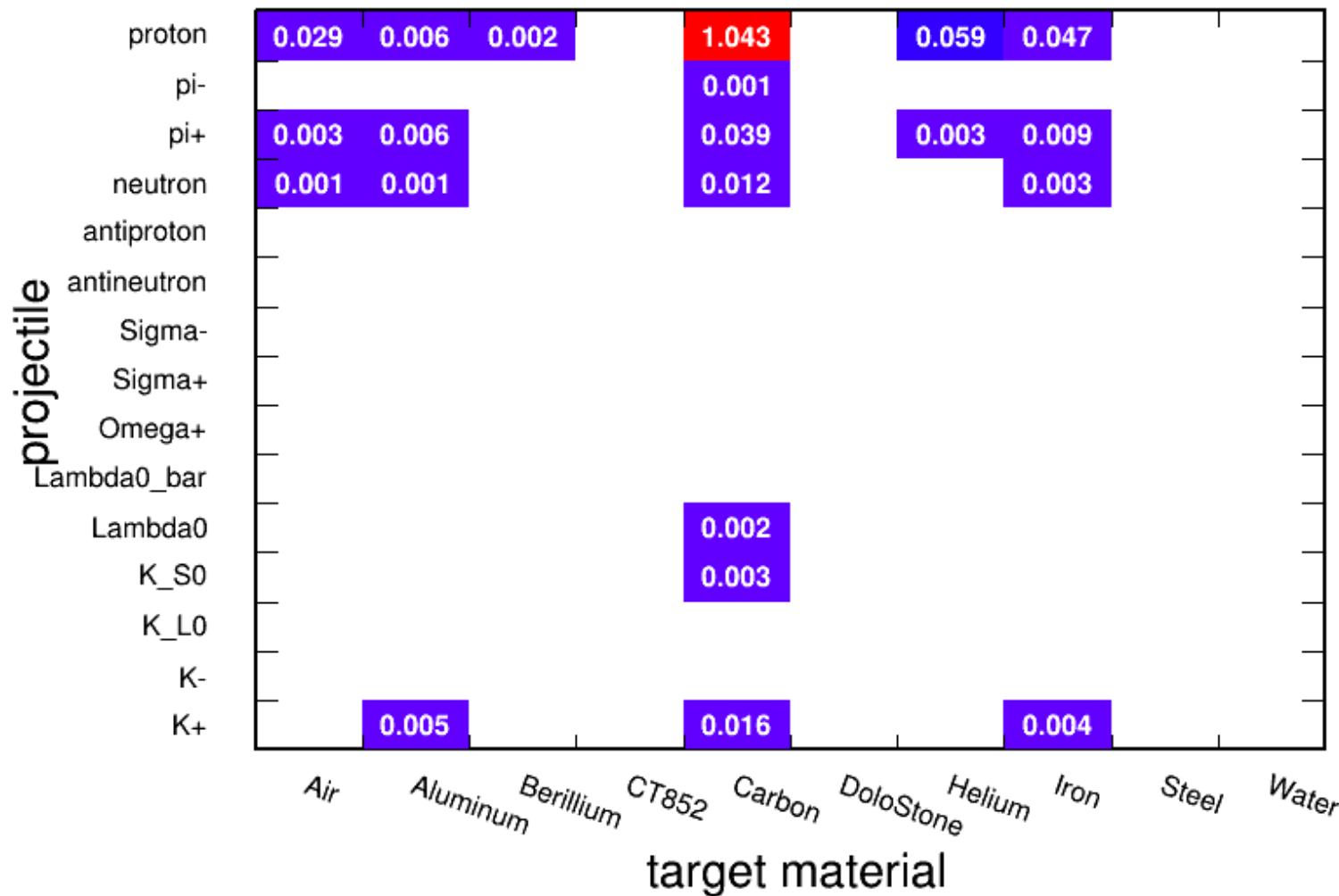


3-4 GeV: π A → X



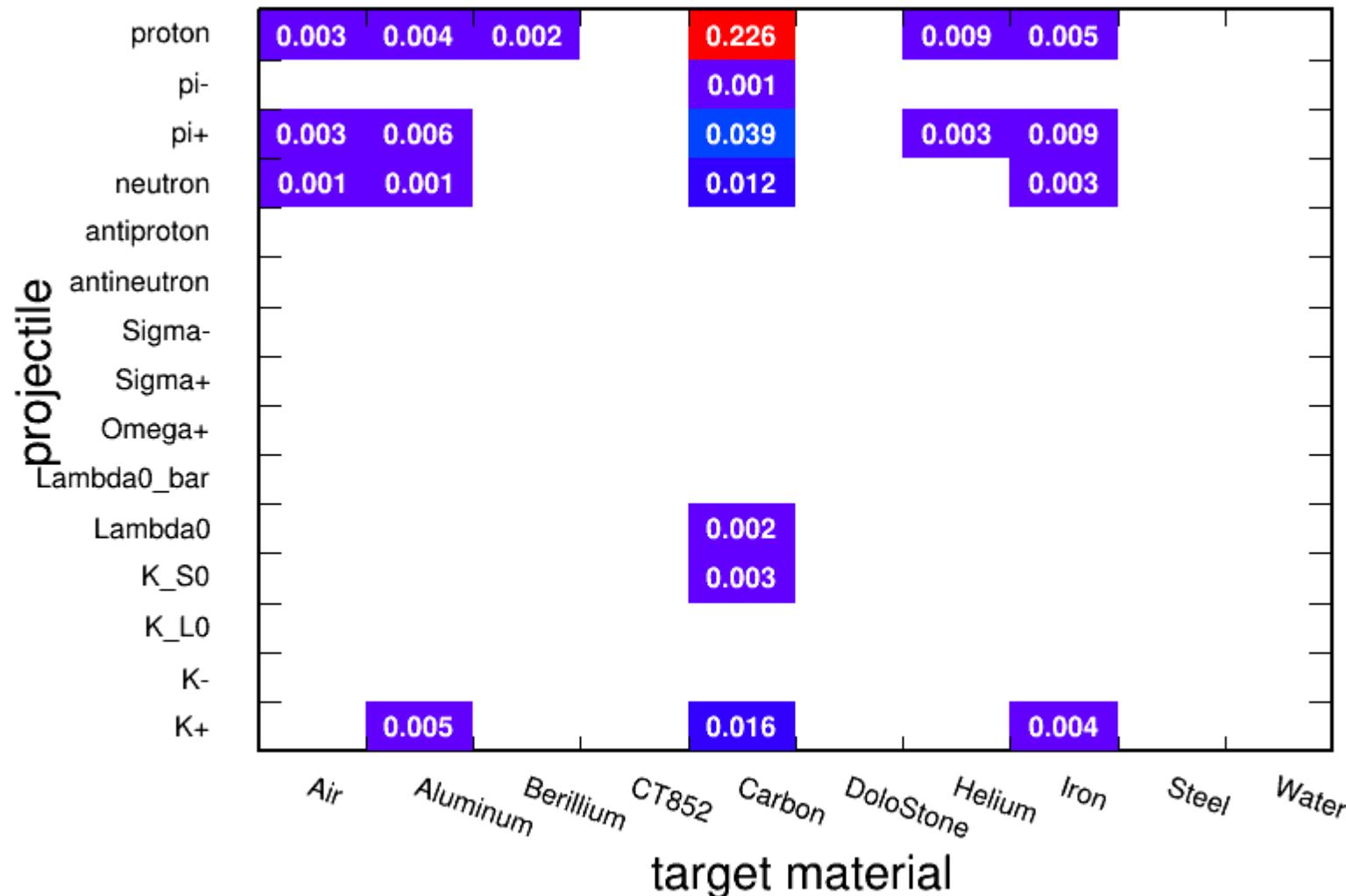
15-16 GeV

Interactions per event

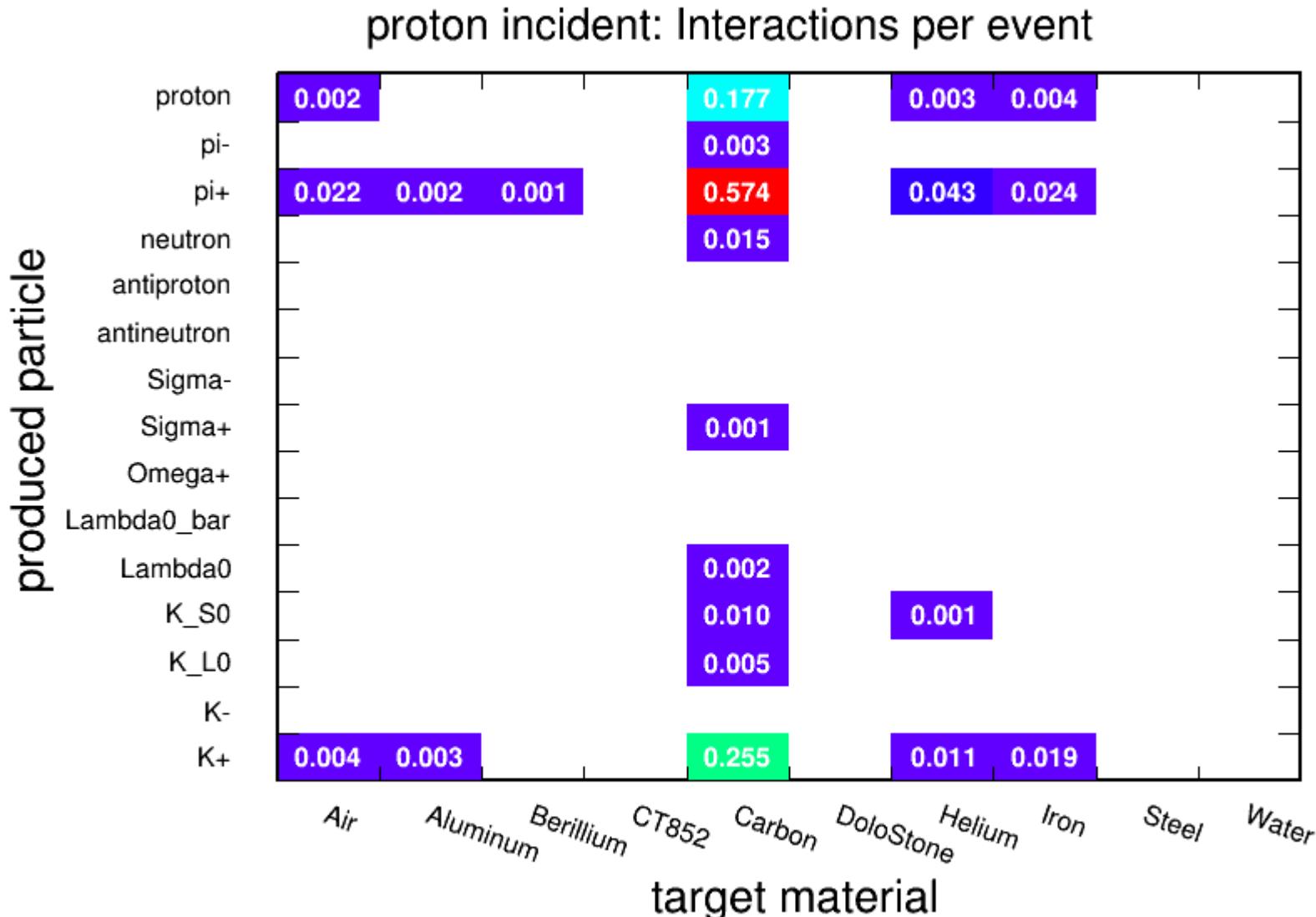


15-16 GeV

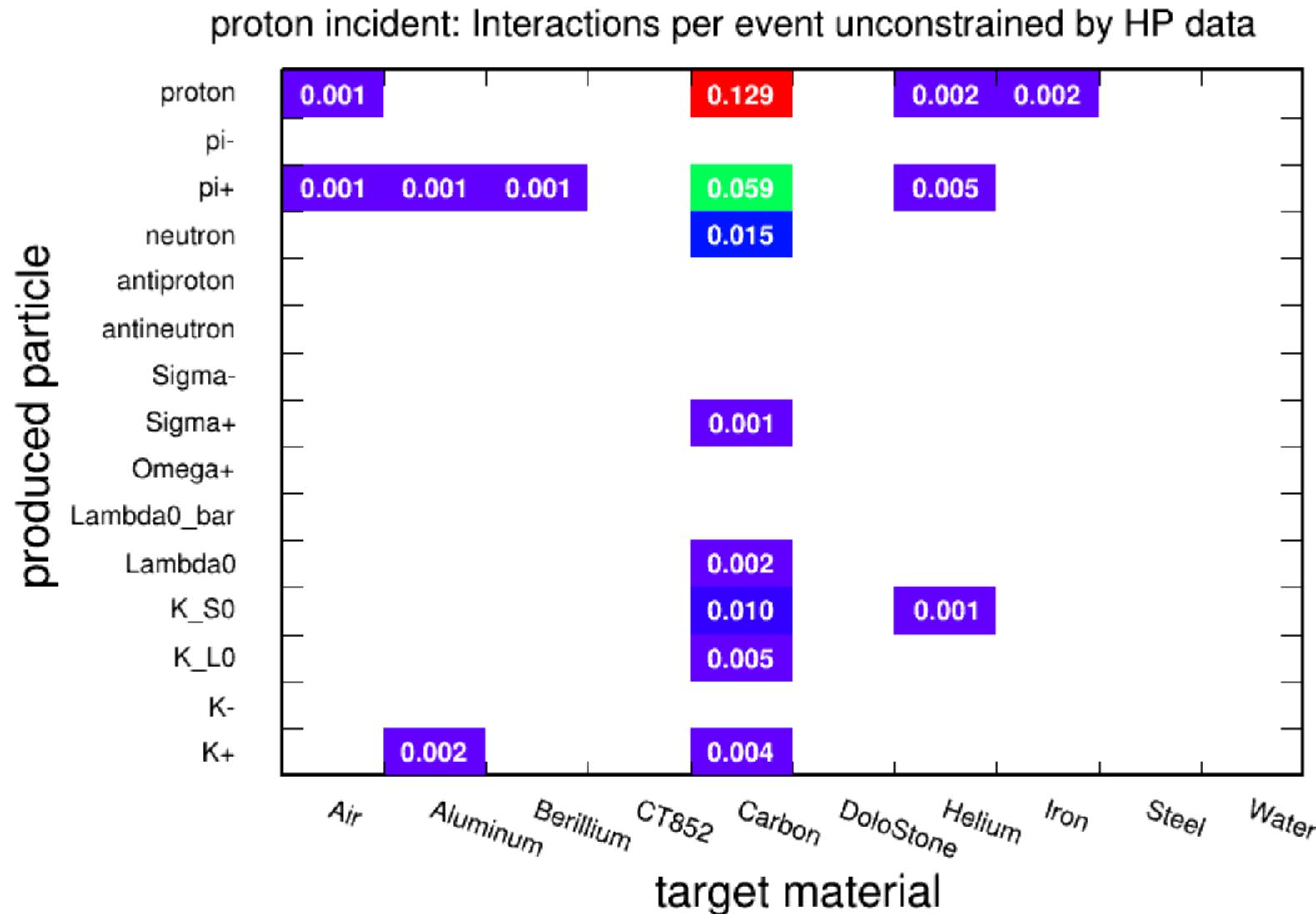
Interactions per event unconstrained by HP data



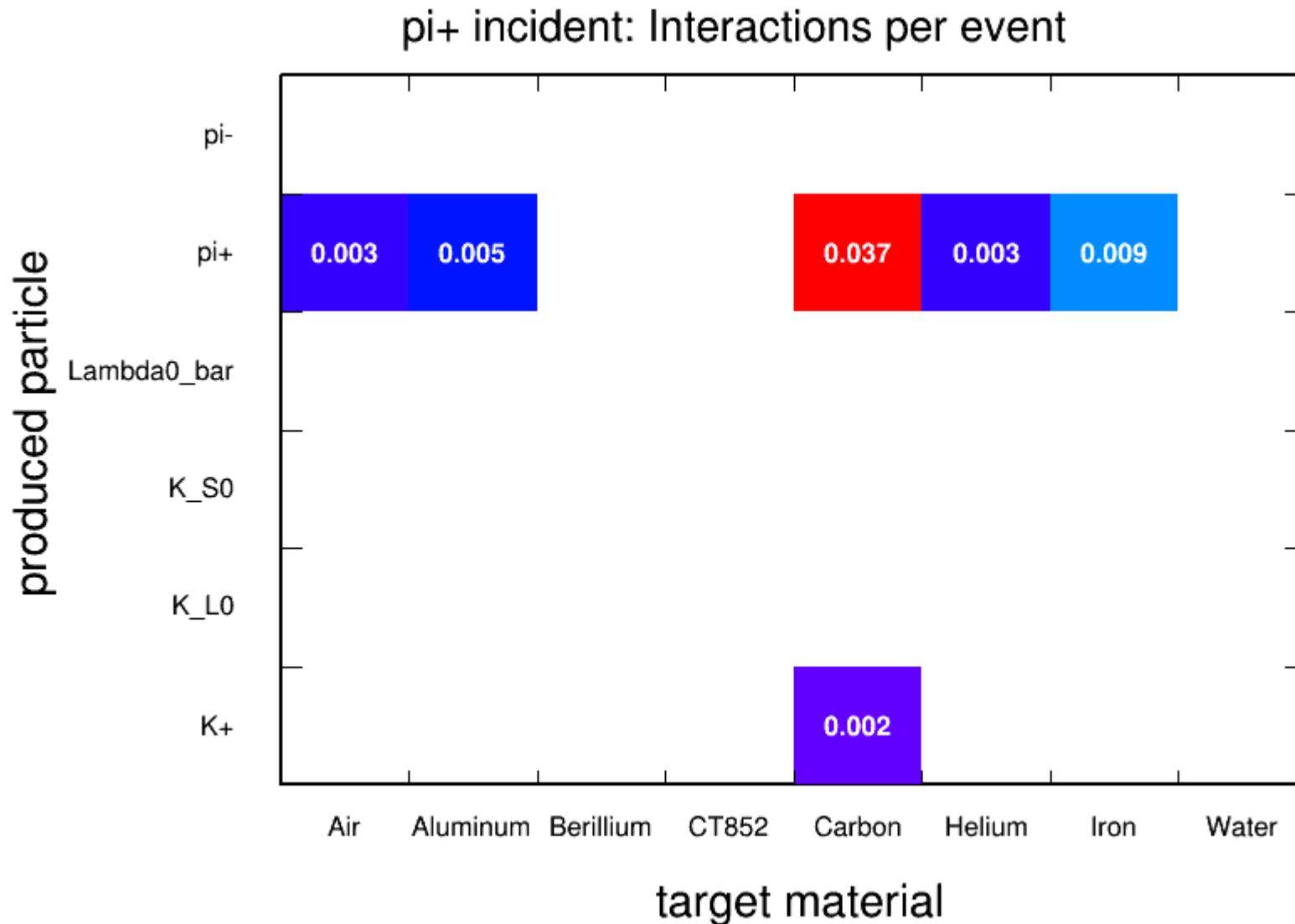
15-16 GeV



15-16 GeV

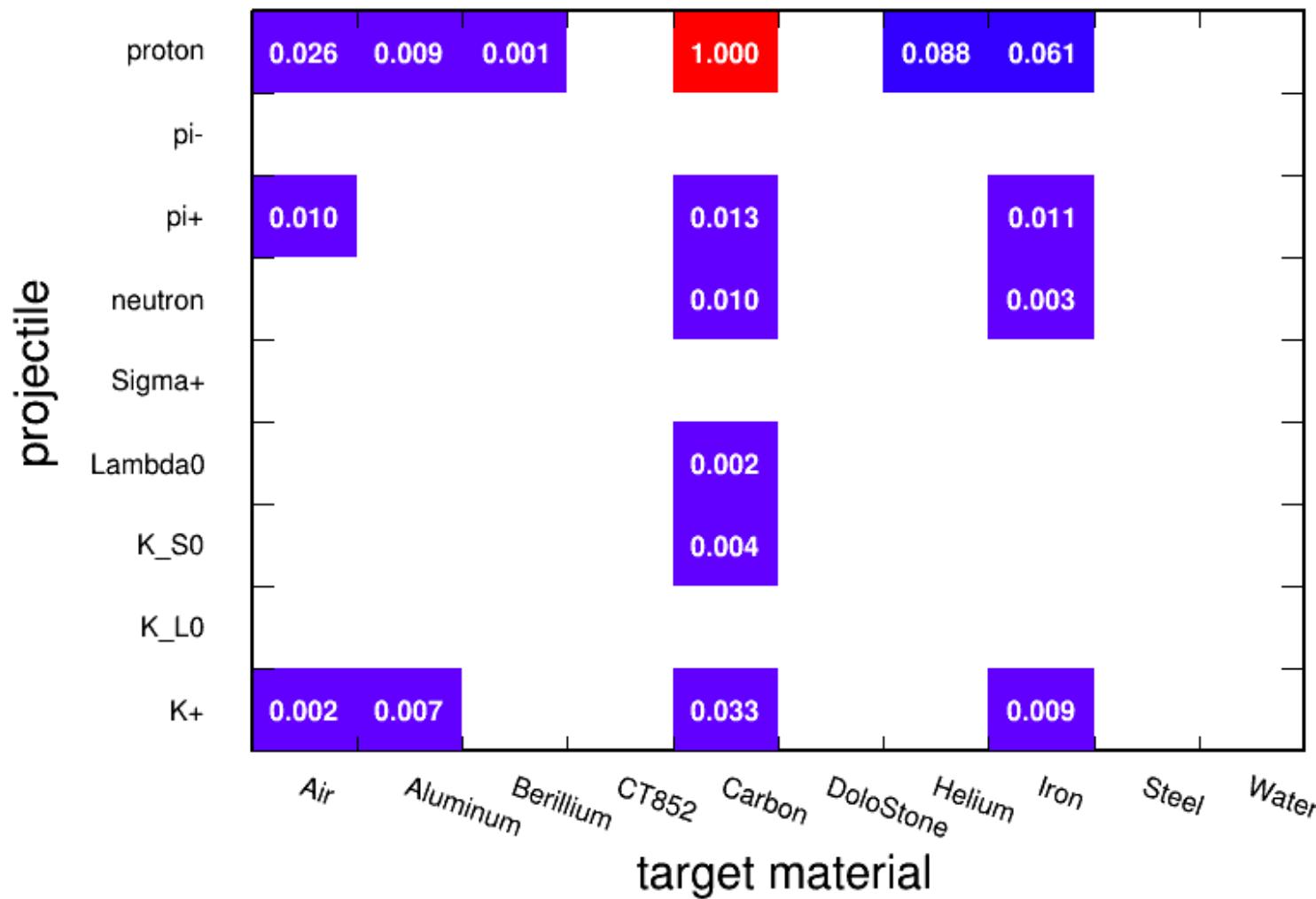


15-16 GeV

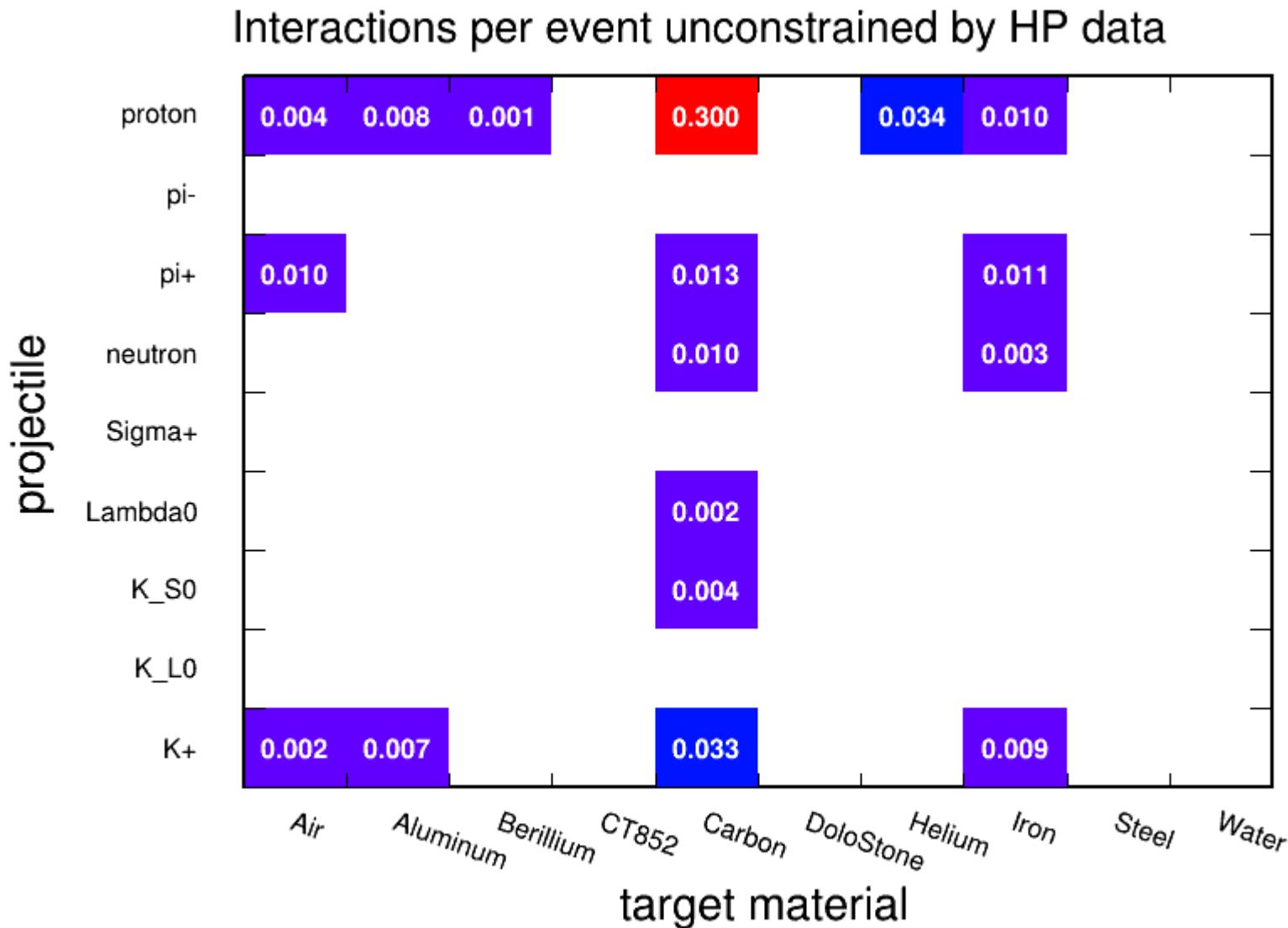


30-31 GeV

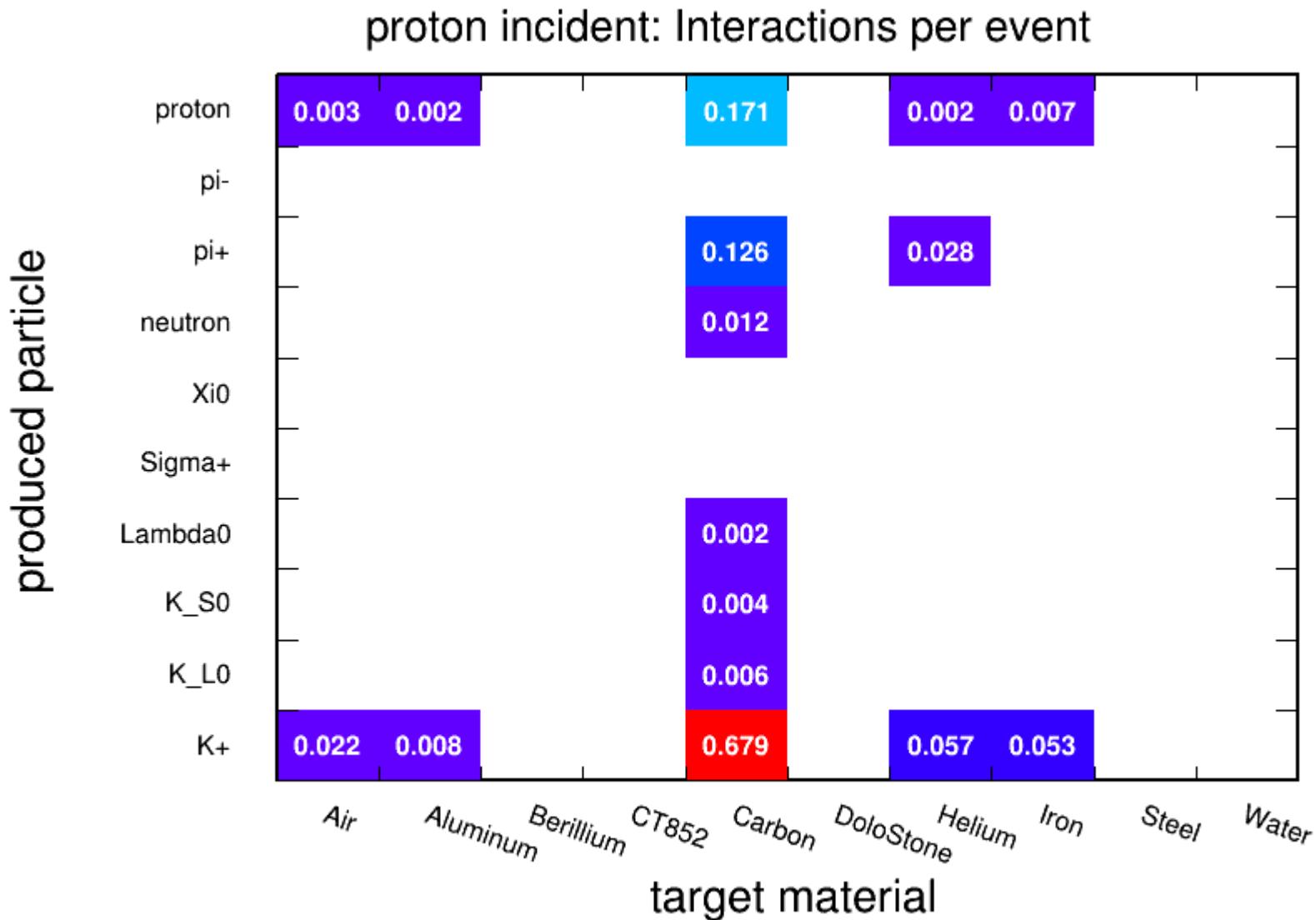
Interactions per event



30-31 GeV

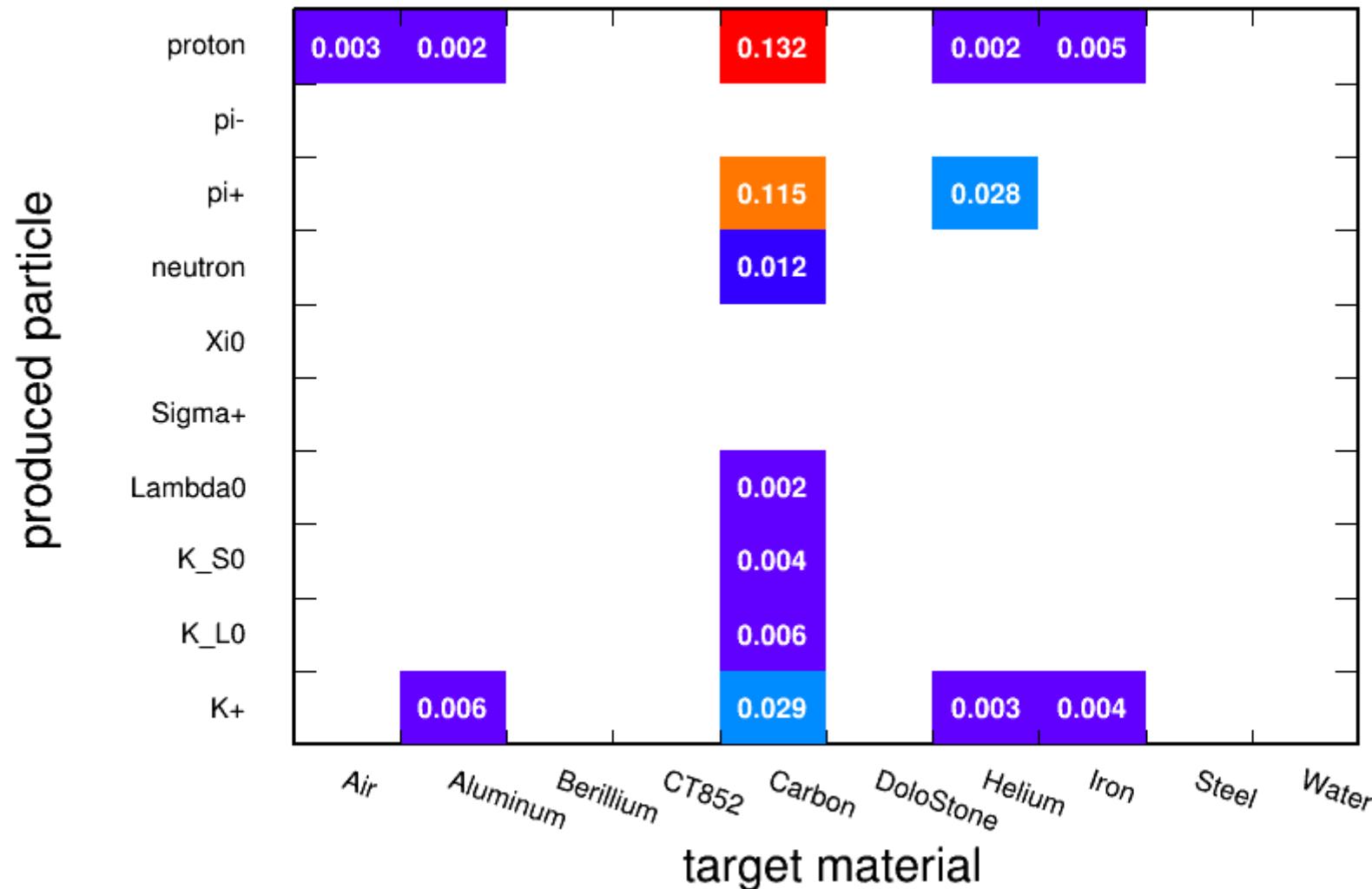


30-31 GeV

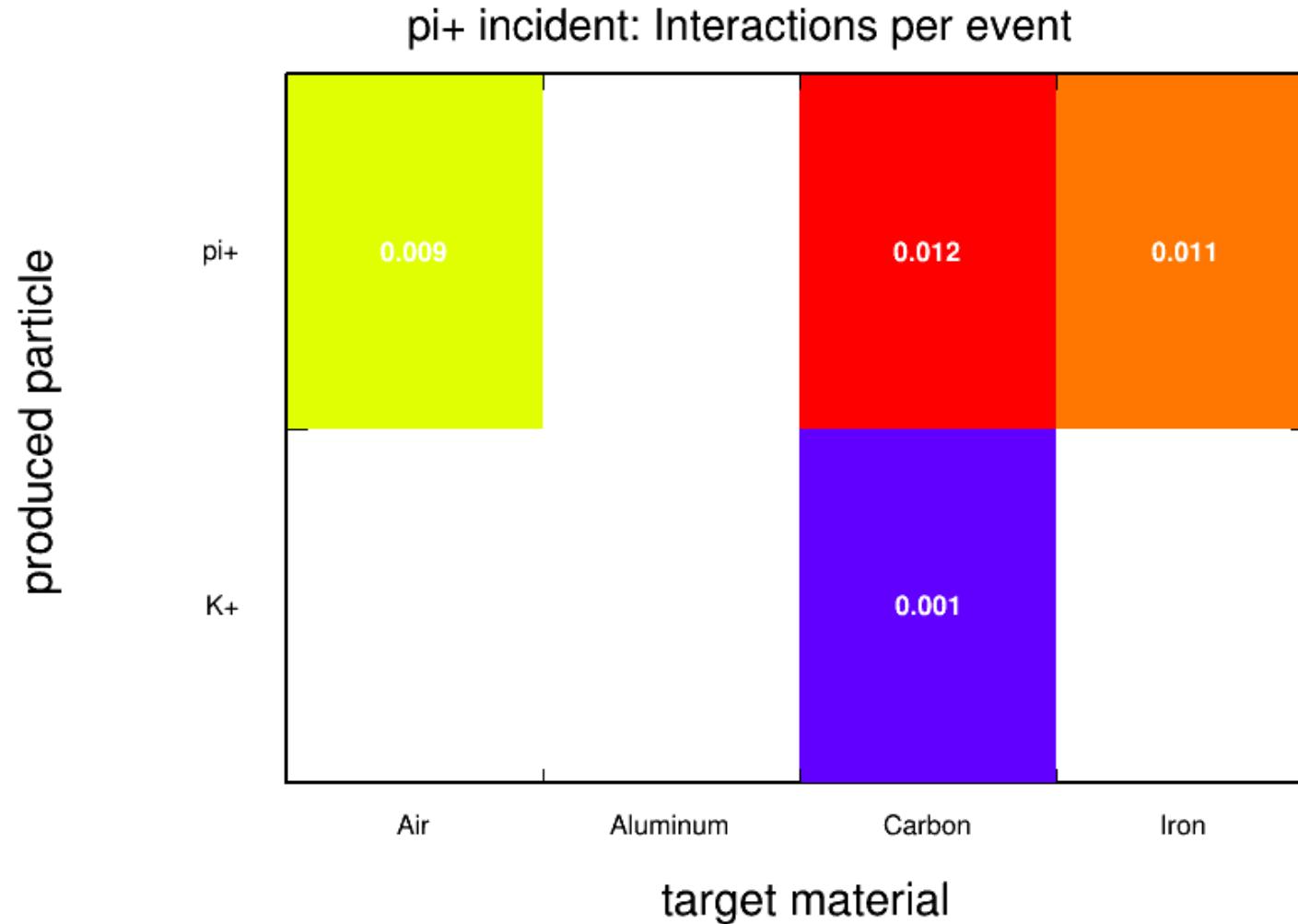


30-31 GeV

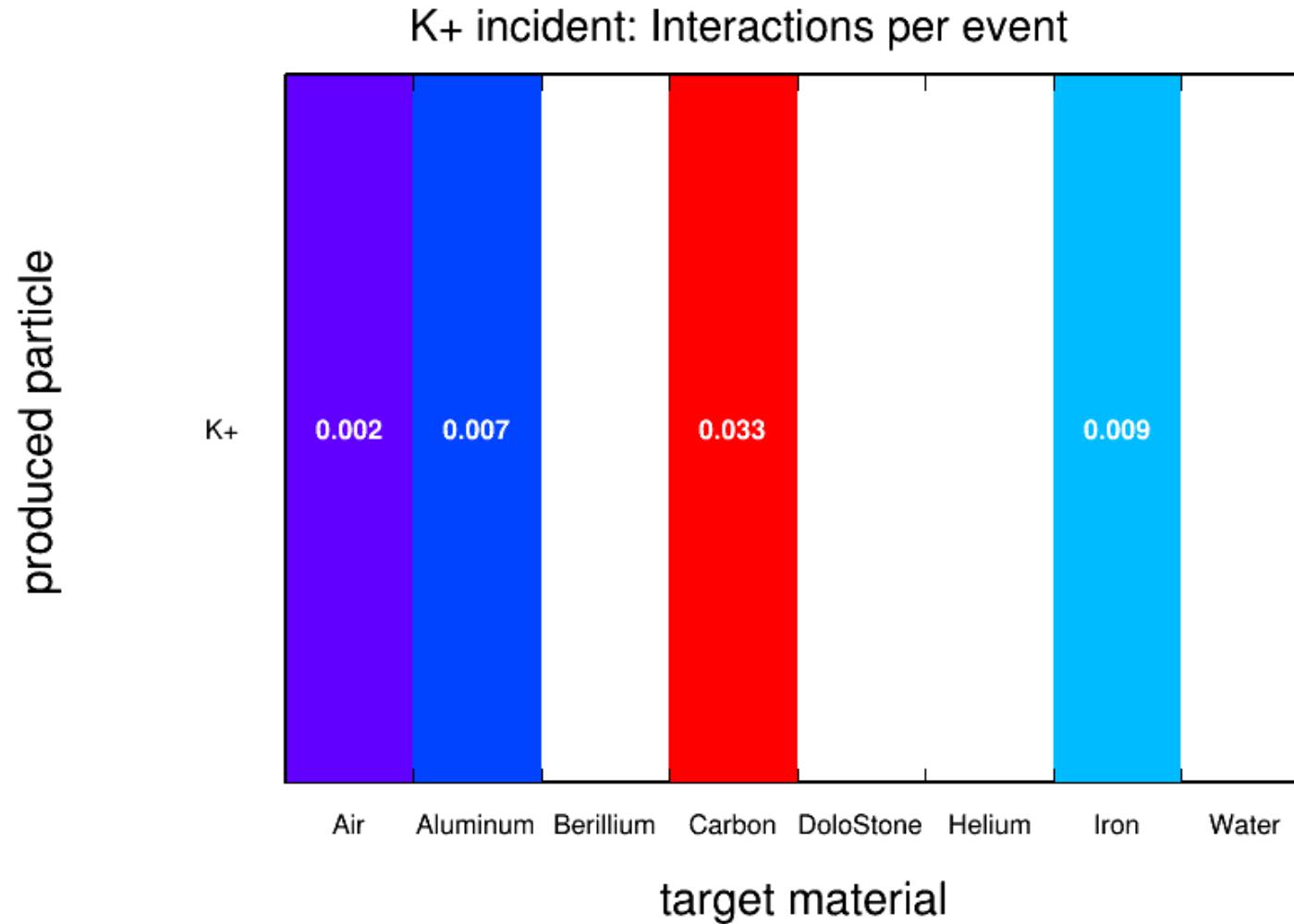
proton incident: Interactions per event unconstrained by HP data



30-31 GeV

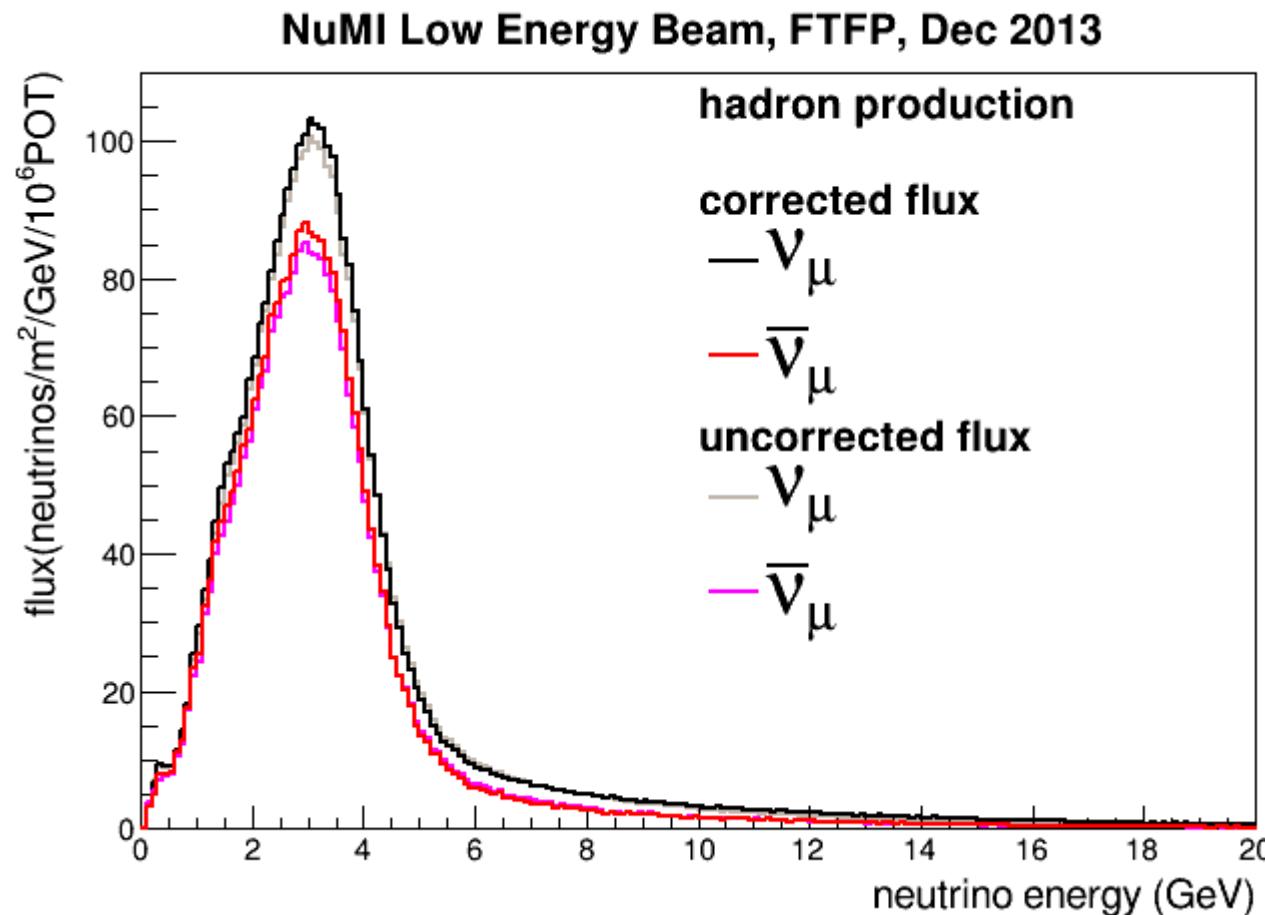


30-31 GeV



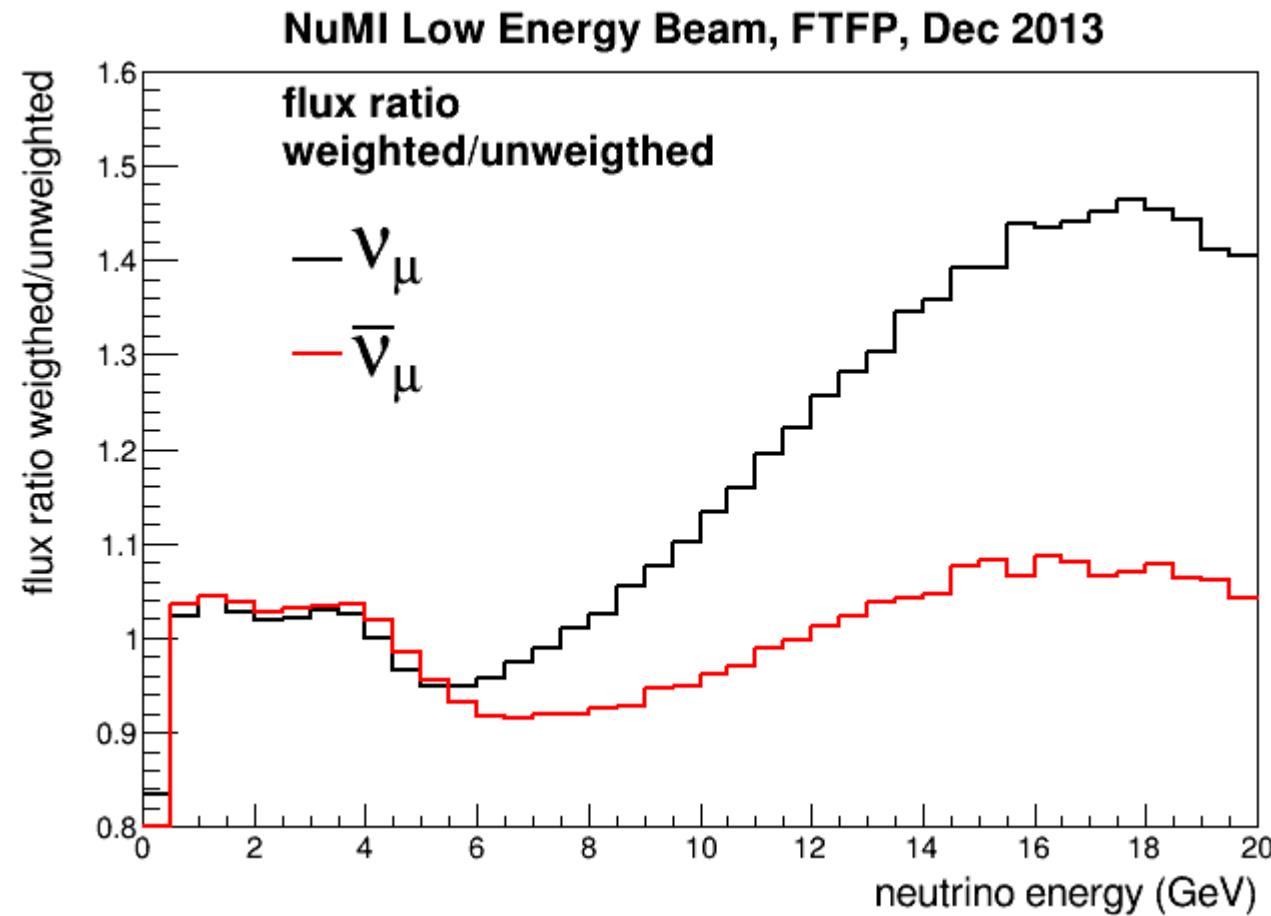
Predicted Flux

LE010z185i & LE010z185i



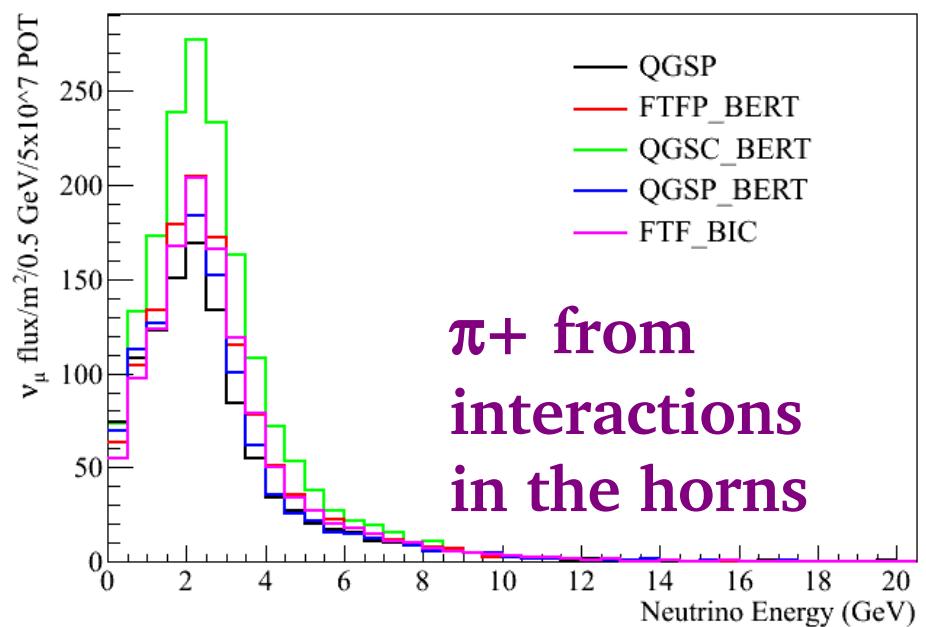
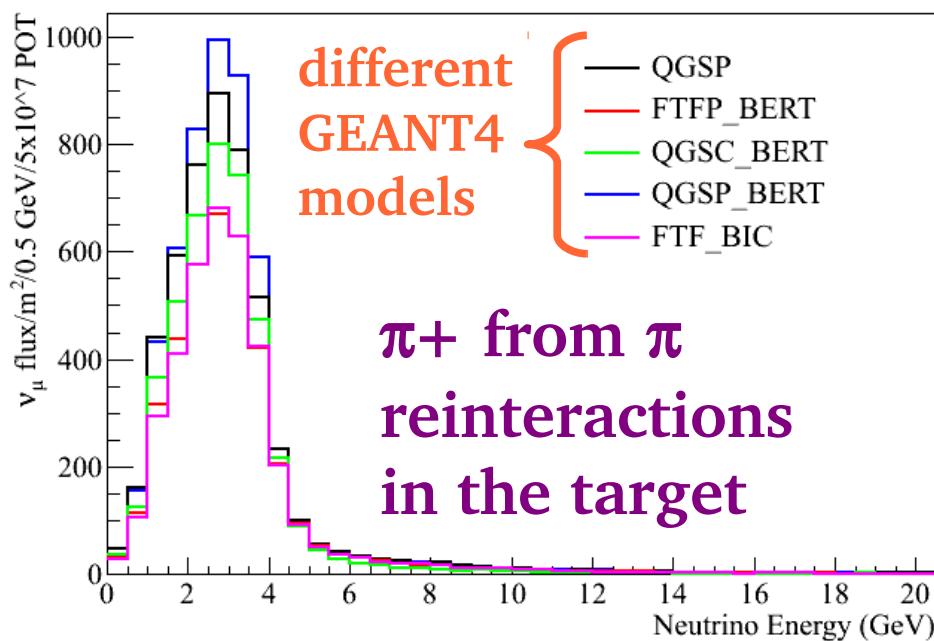
Effect of reweighting on the flux

LE010z185i & LE010z-185i



Model Spread Uncertainties

Non-NA49 uncertainties from maximum model spread



Categories

$\pi, K, p, n, \text{other secondary}$
interactions in target

production in horns, decay pipe
walls & He, target hall chase

Large project to
(a) add more models
(b) gradually replace
model spread with existing
and new data